U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-252 653

UNIVERSITY OF WASHINGTON ELECTROSTATIC SPRAY SCRUBBER EVALUATION

WASHINGTON UNIVERSITY

PREPARED FOR
INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY

APRIL 1976

140249

PB 252 653

EPA-600/2-76-100
April 1976

Environmental Protection Technology Series

UNIVERSITY OF WASHINGTON ELECTROSTATIC SPRAY SCRUBBER EVALUATION

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

EPA REVIEW NOTICE

This report has been reviewed by the U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policy of the Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA-600/2-76-100	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE University of Washington Electrostatic Spray Scrubber Evaluation		5. REPORT DATE April 1976 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Michael J. Pilat and Daniel F. Meyer		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Washington Department of Civil Engineering Seattle, Washington 98195		10. PROGRAM ELEMENT NO. 1AB012; ROAP 21ADL-048 11. CONTRACT/GRANT NO. Grant R-803278
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 12/74-12/75 14. SPONSORING AGENCY CODE EPA-ORD
15. SUPPLEMENTARY NOTES Project officer for this report is D. L. Harmon, Mail Drop 61, Ext 2925.		

16. ABSTRACT The report gives results of an evaluation of the effectiveness of a 1700 cu m/hr (1000 cfm) portable electrostatic spray scrubber in controlling fine particle emissions. The multiple-pass scrubber, designed, constructed, and tested by the University of Washington, combines oppositely charged aerosol particles and water droplets in two water spray towers. Negatively energized aerosol charging sections (coronas) precede each spray tower. The pilot plant was tested on artificially generated dioctyl phthalate (DOP) aerosol and on emissions from a pulverized coal-fired boiler. Collection of a 0.5 micron diameter DOP particle ranged from 10.0 to 99.8%. The 10% test was conducted with all high voltage sources inactive. The overall mass collection efficiency for the two DOP tests was 24.98% and 99.6%, respectively. The boiler emission tests showed a collection efficiency for a 0.5 micron diameter particle ranging from 47.0% to 98.0%. Conditions during the 47.0% test included a low water spray rate. Because of the relatively large inlet size distribution, the overall mass collection efficiency decreased only from 99.58% to 96.09% for the two boiler emission tests.

Coal-fired

17. KEY WORDS AND DOCUMENT ANALYSIS			
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Scrubbers Electrostatics Dust Control Aerosols Coal	Combustion	Air Pollution Control Stationary Sources Fine Particles Collection Efficiency Dioctyl Phthalate Aerosol	13B 21B 07A 20C 07D 21D
18. DISTRIBUTION STATEMENT Unlimited		19. SECURITY CLASS (This Report) Unclassified 20. SECURITY CLASS (This page) Unclassified	21. NO. OF PAGES 77 22. PRICE $5.00/2.25

EPA Form 2220-1 (9-73)

PRICES SUBJECT TO CHANGE

CONTENTS

CONTENTS		iii
LIST OF FIGURES		v
LIST OF TABLES		vii
ACKNOWLEDGEMENTS		viii
I	SUMMARY AND CONCLUSIONS	1
II	RECOMMENDATIONS	3
III	RESEARCH OBJECTIVES	4
IV	EXPERIMENTAL EQUIPMENT AND PROCEDURES	5
	A. Electrostatic Scrubber Apparatus	5
	1. Description of Overall System	5
	2. Cooling Tower	5
	3. Particle Charging Corona Sections	8
	4. Water Spray Towers	10
	5. Demister Section	14
	6. Test Ducts	14
	7. Fan	15
	8. High Voltage Power Supplies	15
	9. Water Supply System	16
	10. Water Drain System	17
	B. Description of Source Test Equipment	17
	1. General	17
	2. UW Mark III Cascade Impactor	17
	3. Water Charge to Mass Ratio	20
	4. Aerosol Charge to Mass Ratio	20
	C. Description of Sources	20

Contents (concluded)

1. Dioctyl Phthalate (DOP) 20
2. Pulverized Coal Fired Boiler 22

V RESULTS 23

A. Test Conditions 23

1. Dioctyl Phthalate 23
2. Coal Fired Boiler 23

B. Particle Collection Efficiency 25

1. Dioctyl Phthalate 25
2. Coal Fired Boiler 25

VI DISCUSSION RESULTS 38

A. Dioctyl Phthalate 38

1. Influence of Gas Residence Time 38
2. Influence of Water to Gas Ratio and Applied Nozzle Voltage 38
3. Influence of Aerosol and Droplet Charging 41

B. Pulverized Coal Fired Boiler 41

1. Influence of Applied Nozzle Voltage 41
2. Influence of Water to Gas Ratio 41

C. Error Analysis 45

VII REFERENCES 47

Appendix A - DOP Test Conditions 48

Appendix B - Pulverized Coal Fired Boiler Test Conditions 57

Appendix C - Error Analysis of Size Dependent Particle Collection Efficiency 61

LIST OF FIGURES

1. General Layout of Electrostatic Scrubber Pilot Plant 6
2. Cooling Tower 7
3. Particle Charging Corona Section 9
4. Collection Plate Flushing System 11
5. Spray Tower #1 Nozzle Configuration 12
6. Spray Tower #2 Nozzle Configuration 13
7. UW Cascade Impactor Sampling Train 19
8. Sampling Train for Aerosol Charge to Mass 21
9. Collection Efficiency vs. Particle Size for DOP Test No. 1 26
10. Collection Efficiency vs. Particle Size for DOP Test No. 2 27
11. Collection Efficiency vs. Particle Size for DOP Test No. 3 28
12. Collection Efficiency vs. Particle Size for DOP Test No. 4 29
13. Collection Efficiency vs. Particle Size for DOP Test No. 5 30
14. Collection Efficiency vs. Particle Size for DOP Test No. 6 31
15. Collection Efficiency vs. Particle Size for DOP Test No. 7 32
16. Collection Efficiency vs. Particle Size for DOP Test No. 8 33
17. Collection Efficiency vs. Particle Size for Coal Fired Boiler Test No. 1 34
18. Collection Efficiency vs. Particle Size for Coal Fired Boiler Test No. 2 35

LIST OF FIGURES (continued)

19. Collection Efficiency vs. Particle Size for Coal Fired Boiler Test No. 3 — 36

20. Influence of Gas Residence Time on Particle Collection Efficiency — 39

21. Influence of Water to Gas Ratio and Water Droplet Charging Voltage on Particle Collection Efficiency — 40

22. Influence of Aerosol and Droplet Charging on Particle Collection Efficiency — 42

23. Influence of Water Droplet Charging Voltage on Particle Collection Efficiency — 43

24. Influence of Water to Gas Ratio on Particle Collection Efficiency — 44

25. Error Bands in the Size Dependent Particle Collection Efficiency Curves — 46

LIST OF TABLES

1.	High Voltage Power Supply Units	15
2.	Source Test Parameters and Measurement Techniques	18
3.	Coal Analysis-As Received Basis	22
4.	Summary of DOP Test Conditions	24
5.	Summary of Coal Fired Boiler Test Conditions	25
6.	DOP Test No. 1 Parameters - Appendix A	49
7.	DOP Test No. 2 Parameters - Appendix A	50
8.	DOP Test No. 3 Parameters - Appendix A	51
9.	DOP Test No. 4 Parameters - Appendix A	52
10.	DOP Test No. 5 Parameters - Appendix A	53
11.	DOP Test No. 6 Parameters - Appendix A	54
12.	DOP Test No. 7 Parameters - Appendix A	55
13.	DOP Test No. 8 Parameters - Appendix A	56
14.	Coal Fired Boiler Test No. 1 Parameters - Appendix B	58
15.	Coal Fired Boiler Test No. 2 Parameters - Appendix B	59
16.	Coal Fired Boiler Test No. 3 Parameters - Appendix B	60
17.	Error Analysis for DOP Test No. 6 - Appendix C	64
18.	Error Analysis for DOP Test No. 7 - Appendix C	65
19.	Error Analysis for DOP Test No. 8 - Appendix C	66

ACKNOWLEDGEMENTS

The authors wish to express their appreciation for the assistance and cooperation of the Project Officer, Mr. Dale Harmon, Chemical Engineer in the Particle Technology Branch of the Environmental Protection Agency.

SECTION I

SUMMARY AND CONCLUSIONS

A 1,700 m^3/hr (1,000 acfm) University of Washington Electrostatic Spray Scrubber pilot plant was designed and constructed inside a 12.2 meter (40 foot long) trailer for use in evaluating the collection efficiency of particulate emissions at field locations. The pilot plant consists of a cooling tower, two corona sections which charge the particles to a negative polarity, two spray towers into which positively charged water droplets are sprayed and an electrostatic mist collector.

The pilot plant was tested on both a dioctyl phthalate (DOP) aerosol and emissions from a pulverized coal fired boiler. The DOP tests showed:

a) 99.8% collection efficiency for a 0.5 micron diameter particle when operating at a gas flow of 569 m^3/hr (335 acfm), particle and droplet charging voltages of -70 kV and +25 kV, respectively and a water to gas ratio of 13.43 gal/1,000 acf.

b) 90% collection efficiency for a 0.5 micron diameter particle when operating at a gas flow of about 1,700 m^3/hr (1,000 acfm), particle and droplet charging voltages of -70 kV and +25 kV, respectively and a water to gas ratio of about 6 gal/1,000 acf.

c) 23.5% collection efficiency for a 0.5 micron diameter particle when operating at a gas flow of 1,648 m^3/hr (970 acfm), particle and droplet charging voltages of 0 and +15 kV, respectively (i.e., uncharged particles and charged droplets) and a water to gas ratio of 6.18 gal/1,000 acf.

d) 10.0% collection efficiency for a 0.5 micron diameter particle when operating at a gas flow of 1,645 m^3/hr (968 acfm), no particle and droplet charging (i.e., operating as a conventional spray tower) and a water to gas ratio of 6.20 gal/1,000 acf.

The tests on the emissions from the coal fired boiler showed:

a) 99.1% collection efficiency for a 0.5 micron diameter particle when operating at a gas flow of 1,694 m^3/hr (997 acfm), particle and droplet charging voltages of -65 kV and +20 kV, respectively and a water to gas ratio of 5.82 gal/1,000 acf. The outlet concentration of the aerosol during this test was 0.002 gr/sdcf.

b) 76.0% collection efficiency for a 0.6 micron diameter particle when operating at a gas flow of 1,801 m^3/hr (1,060 acfm), particle and droplet charging voltages of -60 kV and +20 kV, respectively and a water to gas ratio of 2.36 gal/1,000 acf. The outlet concentration of the aerosol during this test was 0.013 gr/sdcf.

The DOP and coal fired boiler tests showed that the particle collection efficiency increased as:

a) The aerosol and/or droplet changed from an uncharged to a charged state.

b) The gas residence time in the pilot plant increased.

c) The voltage applied on the water droplet spray nozzles increased.

d) The water to gas ratio (i.e., gal/1,000 acf) increased.

In conclusion, it appears that the University of Washington Electrostatic Spray Scrubber has the capability of effectively collecting fine particles in the 0.3 to 1.0 micron diameter size range when operated with water usage rates in the 3-6 gal/1,000 acf range. Further, the system has a significantly higher particle collection efficiency than a conventional water spray tower operating with no electrostatic charging.

SECTION II

RECOMMENDATIONS

After this first year's research project on the U.W. Electrostatic Scrubber which consisted mainly of the design and construction of the portable pilot plant facility, extensive testing at field sites is needed in order to correlate the particle collection efficiency as a function of particle size to the design and operating parameters of this pilot plant.

We also recommend that the results from the extensive field testing program be used in comparison with theoretically predicted particle collection efficiency as a function of size.

Finally, we recommend that the pilot plant be used to demonstrate its effectiveness for simultaneous control of particulate and SO_2 emissions from coal fired boilers.

SECTION III

RESEARCH OBJECTIVES

The objectives of the research performed under the auspices of Environmental Protection Agency Grant Number R803278-01-0 were to:

1. Demonstrate the effectiveness of the University of Washington electrostatic wet scrubber for controlling the emissions of fine particles from coal-fired plants.

2. With a portable 1,700 m^3/hr (1,000 cfm) pilot plant of the University of Washington electrostatic wet scrubber, obtain the data needed to design a larger electrostatic scrubber system.

SECTION IV

EXPERIMENTAL EQUIPMENT AND PROCEDURES

A. ELECTROSTATIC SCRUBBER APPARATUS

1. Description of Overall System

The major components of the pilot plant include a gas cooling tower, an inlet and outlet test duct, two particle charging corona sections, two charged water droplet spray towers and a demister. Auxiliary equipment includes transitional ductwork between major components and a fan. The pilot plant is housed in a 12.2 meter (40 foot) long trailer and can be easily transported to different emission sources.

The general layout of the pilot plant is shown in Figure 1. Incoming gases enter the top of the trailer to be treated in the vertical gas cooling tower and then turn vertically upward to enter the inlet test duct. After moving down through the inlet test duct, the gases enter the first of three horizontal passes.

The first pass contains both particle charging corona sections and the first of two water spray towers. The two coronas are at either end of this pass and are separated by spray tower #1. Spray tower #2 comprises the entire second horizontal pass and the last (third) pass contains the demister.

At the outlet of the third horizontal pass, the gases enter the top of the outlet test duct and are then directed to the fan before being exhausted through the trailer roof.

2. Cooling Tower

The cooling tower is designed to lower the gas temperature to below 121°C (250°F) in order to maintain structural integrity of the system which is constructed of steel and fiberglass reinforced plastic. The cooling tower, as shown in Figure 2, is 0.36 meters (14 inches) in diameter x 2.98 meters (9 feet - 8 inches) in height and is constructed of

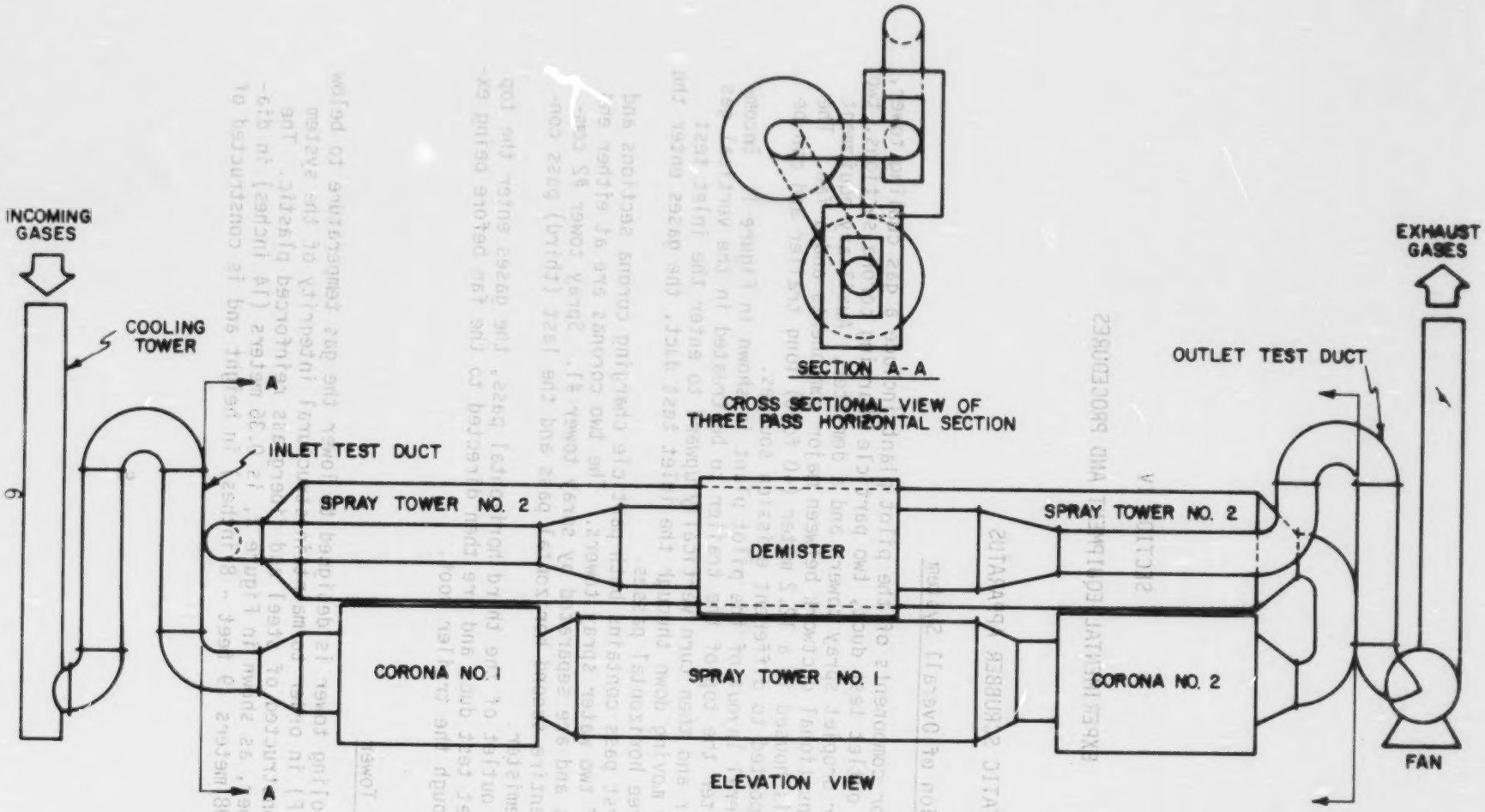

FIGURE 1. GENERAL LAYOUT OF ELECTROSTATIC SCRUBBER PILOT PLANT

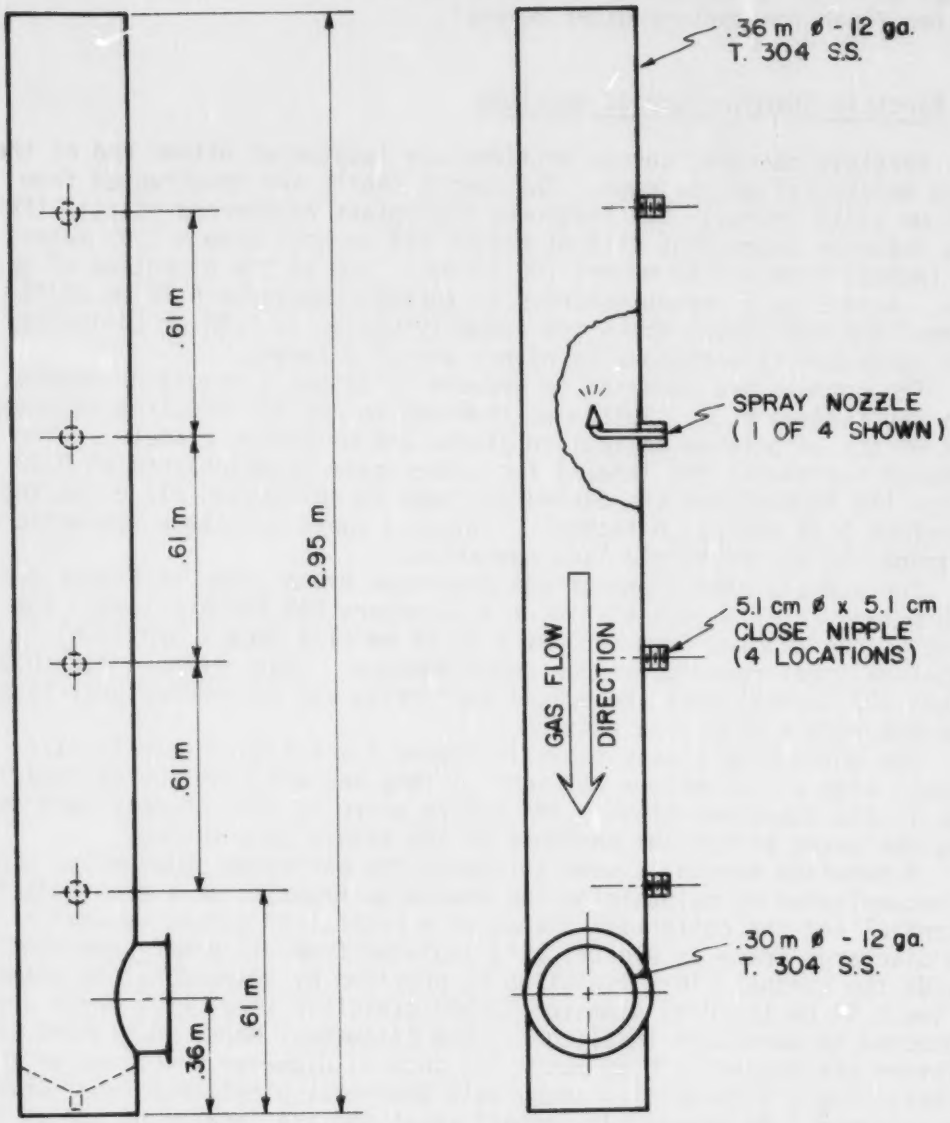

FIGURE 2. COOLING TOWER SCHEMATIC

12 gage T. 304 stainless steel. Cooling water is introduced through four ports spaced at 0.61 meter (2 feet) intervals on one side of the tower and is sprayed vertically upward from the tower's centerline. Four Bete Model W 10080 F full cone stainless steel nozzles used for spraying are capable of delivering up to 11.35 liters/min (3.0 gpm) at 50 psig. A funnel built into the bottom of the spray tower extends through the trailer floor for cooling water removal.

3. Particle Charging Corona Sections

Particle charging corona sections are located at either end of the first horizontal gas passage. The corona shells are constructed from 4.76 mm (3/16 inches) wall thickness fiberglass reinforced plastic (FRP) with interior dimensions of 0.61 meters (24 inches) wide x 1.07 meters (42 inches) high x 1.52 meters (60 inches) long in the direction of gas flow. Access to a corona interior is through removable 4.76 mm (3/16 inches) FRP end plates which are normally bolted to 5.08 cm (2 inches) full perimeter face flanges on either end of a corona.

The coronas are designed to operate in either a single or double lane gas passage mode. Switching from one to another requires rearrangement of the adjustable collection plates and discharge frame(s). The width of individual gas lane(s) for either mode is maintained at 0.30 meters (12 inches) and the discharge frame to collection plate spacing is therefore 0.15 meters (6 inches). Figure 3 shows a cutaway schematic of a corona set up for single lane operation.

The overall dimensions of the discharge frame shown in Figure 3 are 0.70 meters (27-1/2 inches) high x 1.14 meters (45 inches) long. The frame is constructed from 6.35 mm x 19.05 mm (1/4 inch x 3/4 inch) T. 304 stainless steel rectangular bar stock members. Eight members each 0.69 meters (27 inches) high are spaced vertically and perpendicularly to gas flow and form a grid type pattern.

The collection plates shown in Figure 3 are 1.05 meters (41-1/4 inches) high x 1.50 meters (59 inches) long and are constructed from 11 gage T. 316 stainless steel. The plates serve as full chamber baffles to keep the gases within the confines of the single lane passage.

A negative corona is used to charge the particles negatively. This is accomplished by maintaining the discharge frame(s) at a high negative potential and the collection plates at a neutral or ground potential. The discharge frame is electrically isolated from all other components inside the corona. This isolation is provided by suspending the frame on two 2.54 cm (1 inch) diameter T. 303 stainless steel rods which are connected to porcelain insulators. The Ceramaseal Model 902B1353-6 insulators are housed in 0.30 meter (12 inches) diameter x 0.61 meter (24 inches) long x 6.35 mm (1/4 inch) wall thickness plexiglass tubes which are centered 1.07 meters (42 inches) apart and are located on top of the corona shells. Two 0.30 meter (12 inches) to 0.36 meter (14 inches) x 7.62 cm (3 inches) FRP reducting flanges are used to join the plexiglass

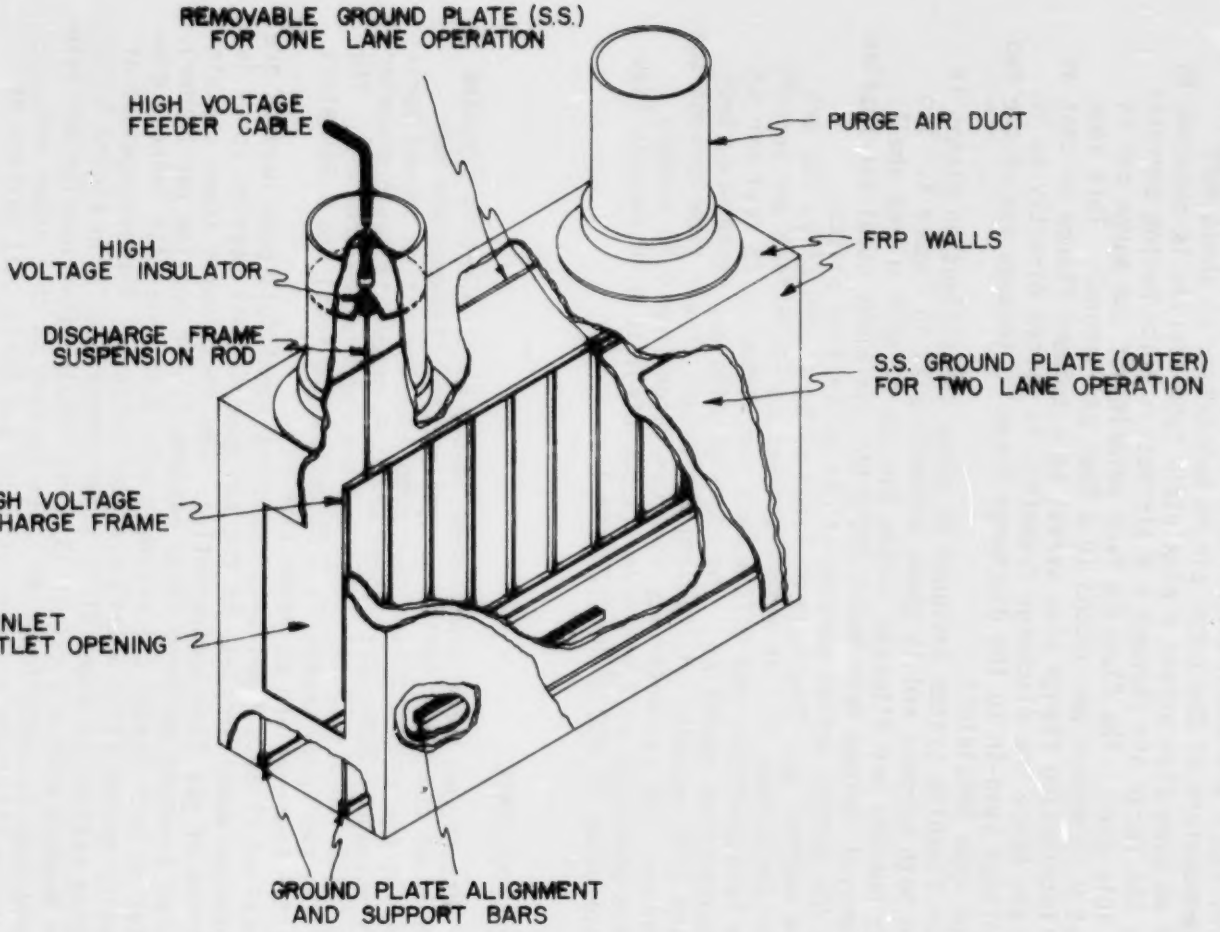

FIGURE 3. PARTICLE CHARGING CORONA SECTION

tubes to the corona top.

The insulators are continually flushed with a supply of heated purge air. The temperature of the purge air is maintained at about 49°C (120°F) and an even flow across a plexiglass tube section is obtained by introducing the purge air through a distribution plate having approximately 10% hole area. The flushing face velocity of the purge air is set at about 0.18 meters per second (0.6 feet per second). This same purge air distribution flange also serves as a support flange in that an insulator, and hence the discharge frame(s), is bolted directly to it. The high voltage lead-in to the discharge frame is through one of the two feed-through type insulators.

A water flushing system designed to clean the collection plates is utilized in both coronas and is shown schematically in Figure 4. Two water spray headers are situated inside the top of each corona shell. Water is sprayed through Bete Model 45080 80° stainless steel fan nozzles and covers the entire active portion of the collection plates.

At the nominal gas flow rate of 1,700 m^3/hr (1,000 cfm), the gas velocity in the corona is 1.45 meters per second (4.76 feet per second) for single lane operation and 0.72 meters per second (2.38 feet per second) for double lane operation. The corresponding gas residence times are 1.05 and 2.10 seconds. By varying the volume of air flow through the system, however, the gas residence time can range from 0.70 seconds (single lane operation at 2,548 m^3/hr (1,500 cfm)) to 4.20 seconds (double lane operation at 850 m^3/hr (500 cfm)).

4. Water Spray Tower

The first of two spray towers used in the pilot plant is situated in the middle of the first horizontal gas passage (between the two coronas) while the second spray tower comprises the entire second horizontal gas passage. Both spray tower are 0.91 meters (3 feet) diameter x 4.76 mm (3/16 inch) wall thickness and are constructed from FRP. The length of the two spray towers is 3.05 meters (10 feet) and 7.36 meters (24 feet) for tower #1 and #2 respectively.

A total of 27 Bete Model L-40 stainless steel full cone nozzles are used to produce water droplets in the two towers. All nozzles spray in the direction of gas flow (cocurrently). The first spray tower contains nine nozzles arranged on three spray headers (three nozzles per header). The nozzles on each header are arranged on a 0.46 meter (18 inches) diameter equally spaced (120° apart) circular pattern. The arrangement of the spraying pattern in tower #1 is shown schematically in Figure 5.

Nine headers with a total of 18 spray nozzles (two nozzles per header) are employed in spray tower #2. The nozzles in this tower are arranged in an alternately spaced vertical and horizontal pattern as shown in Figure 6.

A positive charge is imparted to the water droplets by maintaining the nozzles at a positive potential (direct charging). The nozzles are electrically isolated from the spray tower walls by introducing heated

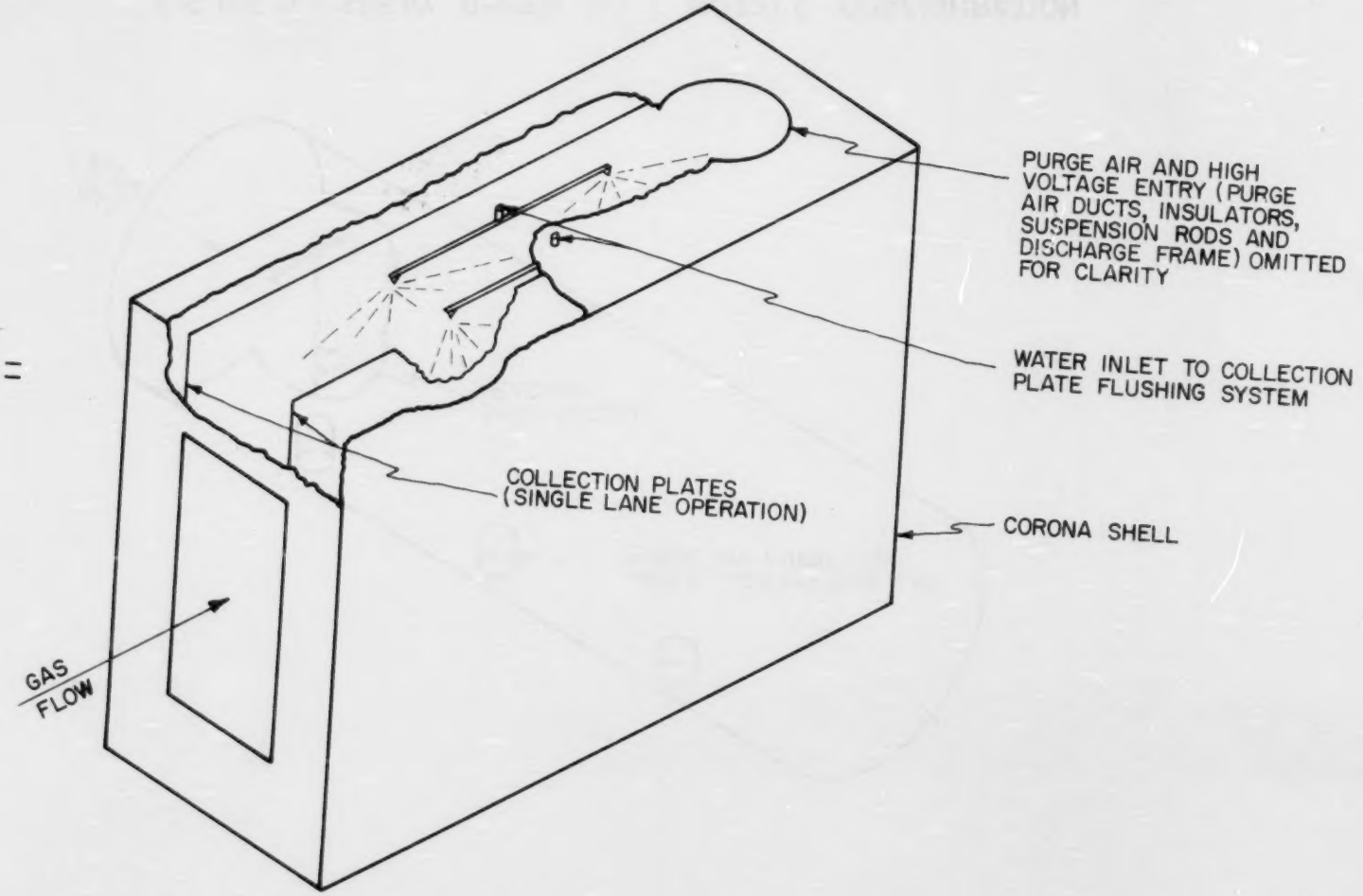
PURGE AIR AND HIGH VOLTAGE ENTRY (PURGE AIR DUCTS, INSULATORS, SUSPENSION RODS AND DISCHARGE FRAME) OMITTED FOR CLARITY
WATER INLET TO COLLECTION PLATE FLUSHING SYSTEM
COLLECTION PLATES (SINGLE LANE OPERATION)
CORONA SHELL
GAS FLOW

FIGURE 4. COLLECTION PLATE FLUSHING SYSTEM

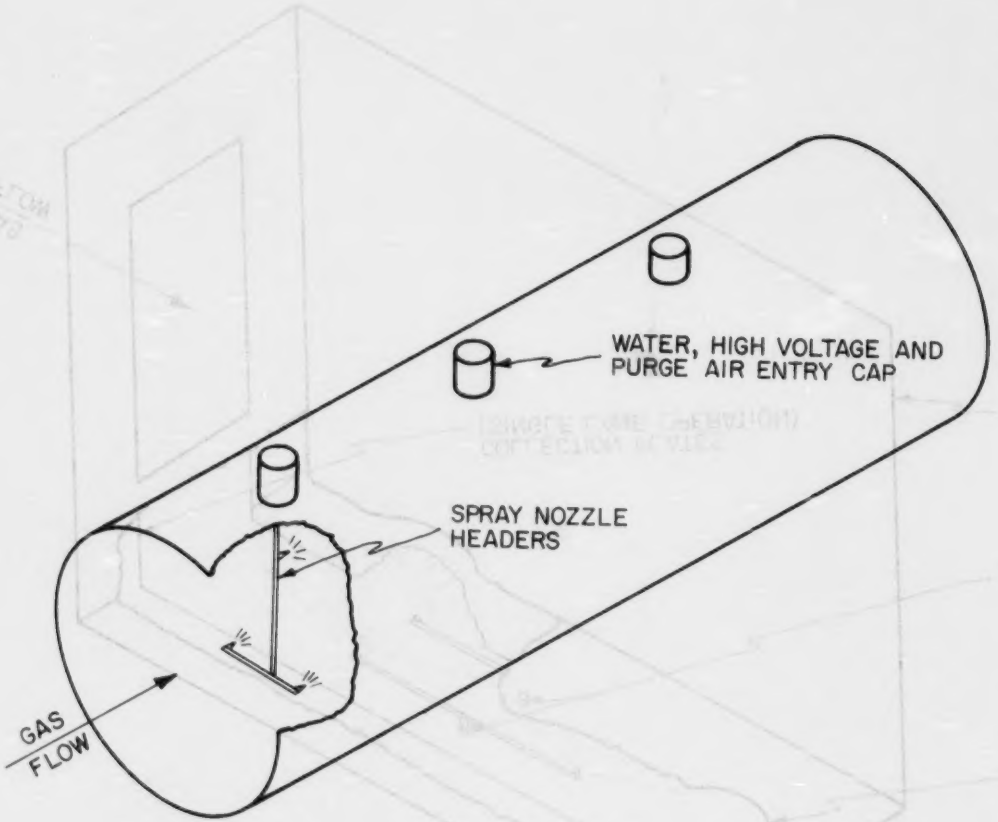

FIGURE 5. SPRAY TOWER NO. 1 NOZZLE CONFIGURATION

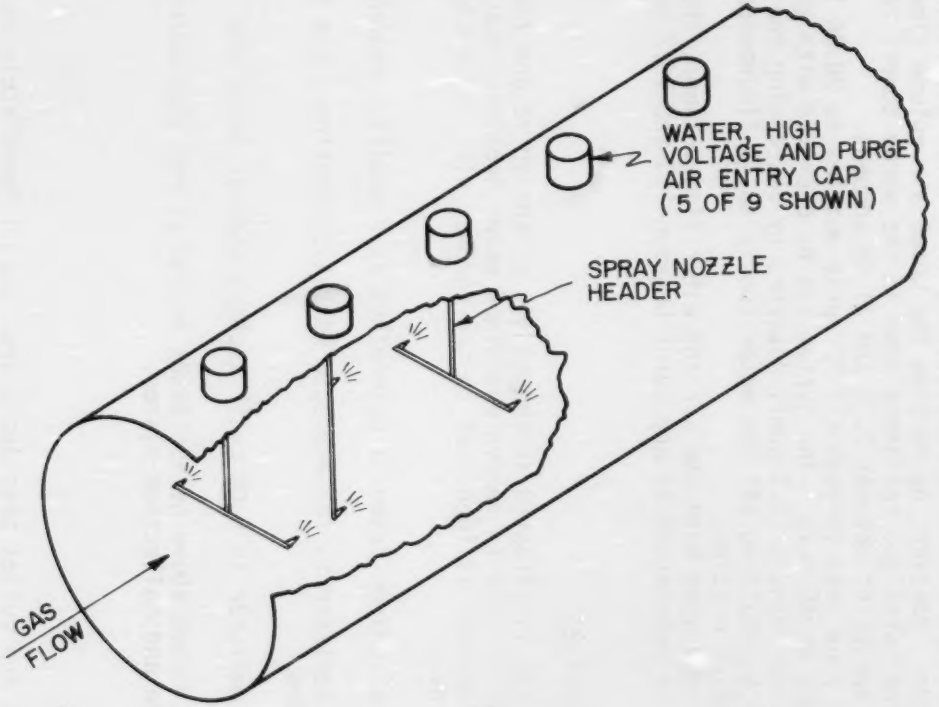

FIGURE 6. SPRAY TOWER NO. 2 NOZZLE CONFIGURATION

purge air through 7.62 cm (3 inches) diameter x 10.16 cm (4 inches) long polyvinyl chloride (PVC) entry caps which are situated on top of the two spray towers (see Figure 5 and 6). Both the water and the high voltage lead-in cable enter through a 6.35 mm (1/4 inch) diameter street tee fitting connected to the middle of each entry cap. Individual spray nozzle headers are also attached to the entry caps.

At the nominal air flow volume of 1,700 m^3/hr (1,000 cfm), the gas velocity inside the spray towers is 0.72 meters per second (2.35 feet per second). This corresponds to a gas residence time of 4.21 and 10.21 seconds in spray towers #1 and #2 respectively or a total gas residence time of 14.46 seconds. However, by varying the total air volume flow in the pilot plant, the total gas residence time in the spray towers can be maintained at any point between 7.23 and 21.69 seconds.

The water flow rate through all 27 spray nozzles is 28.76 liters per minute (7.6 gpm) at 40 psig. The system can be operated with as little as 8.33 liters per minute (2.2 gpm), however, by decreasing the pressure to 20 psig and by shutting off the water supply to 16 (independently controlled) of the 27 nozzles.

Thus, by adjusting both the air and water flow volumes, the water to gas ratio can be maintained at any point between 1.5 and 15.2 gal/1000 acf.

5. Demister Section

The demister is situated in the middle of the third and last horizontal pass and is used to remove entrained water droplets from the air stream. The demister is identical to the coronas with the following three exceptions:

(a) The discharge frame is maintained at a positive potential.

(b) The demister is not equipped with a collection plate flushing system.

(c) The demister is 5.08 cm (2 inches) shorter in height.

The last point noted above necessitates an equivalent shortening of the discharge frame and collection plates.

6. Test Ducts

The inlet and outlet test ducts are located immediately before the first corona and immediately after the demister respectively (see Figure 1). Both test ducts are constructed from 4.76 mm (3/16 inch) wall thickness FRP and are 0.30 meter (12 inches) diameter x 1.22 meters (4 feet) long. Vertical gas flow in a downward direction is employed because it

allows the most convenient positioning of the particle sizing source test equipment used and described in Section IV-B, Description of Source Test Equipment. The particle sizing source test equipment also dictated the size of the test ports which are 7.62 cm (3 inches) wide x 15.24 cm (6 inches) high. The test ports are located three duct diameters downstream and one duct diameter upstream from flow disturbances.

7. Fan

The fan used to induce the air flow (i.e., clean side) through the pilot plant is a New York Blower Model RFE-12. The straight bladed fan wheel and housing are constructed from FRP. The fan is driven through a split pulley belt drive by a Westinghouse 5 HP, 208 volt, 3 phase motor turning at 1,800 rpm and is capable of delivering up to 2,548 m^3/hr (1,500 cfm) at 20.32 cm (8 inches) water column (WC) static pressure. The fan has a horizontal inlet and a vertical outlet. A 4.76 mm (3/16 inch) FRP wall thickness x 0.30 meter (12 inches) diameter exhaust duct containing an adjustable damper extends up through the trailer roof.

8. High Voltage Power Supplies

Three high voltage power supply units used in the pilot plant serve the coronas, demister and water droplet charging. All three units operate off a 110 V, 60 Hz, 1 Ø supply and are equipped with multirange voltage and current meters on the high voltage output side. The units are also equipped with overvoltage and overcurrent surge protection. The three power supplies are described in the following table.

Table 1. HIGH VOLTAGE POWER SUPPLY UNITS

Source	Model	Polarity	Rated Output	
			kV	mA
Coronas	Universal Voltronics BAC - 70 - 25	Negative	70	25
Demister	Hipotronics #860-16	Positive	60	16
Droplet Charging	Hipotronics #825-40	Positive	25	40

A Model P-30 spark rate controller manufactured by L. L. Little,

Inc. is capable of maintaining the spark rate in the coronas at any preset level up to 500 sparks per minute.

9. Water Supply System

All water usage and monitoring is controlled from a single control board situated on an interior trailer side wall proximate to the inlet test duct. Before reaching the control board, however, incoming water passes through a filter and a Watts Model U-5 pressure reducing valve with a controllable outlet set point between 25-75 psig. Water then passes through a main flow meter (7.6 - 75.6 liters per minute (2-30 gpm) Fisher-Porter Model 2235597 Ratosight rotometer) and a 2.54 cm (1 inch) true union PVC ball valve which acts as a main shut off valve. From the main shut off valve, the water enters a 2.54 cm (1 inch) diameter PVC pipe which serves as a supply manifold for seven water applications in the trailer. The seven take-offs from the supply manifold are through 1.27 cm (1/2 inch) diameter PVC pipes and all seven are equipped with true union PVC ball valves and 0-60 psig pressure gages. The seven water users are described below:

(a) Test duct cleaning system

One Bete Model W10080 F full cone stainless steel spray nozzle is positioned at the top of both the inlet and outlet test ducts. Since only infrequent cleaning is required at these two locations, water flow rate is not monitored.

(b) Corona collection plate flushing system

The details of these two users have been specified in Section IV.A.3. - Particle Charging Corona Sections. Again, flow is not monitored due to infrequent use.

(c) Cooling tower spray system

This user, described in Section IV.A.2. - Cooling Tower, is equipped with a Fisher-Porter Model 2235621 3.8 - 41.6 liters per minute (1-11 gpm) Ratosight rotometer.

(d) Water spray towers

Water usage in each of the two water spray towers is controlled from two supply lines. This is accomplished by splitting the flow above the flow meter which is positioned on the 1.27 cm (1/2 inch) diameter PVC pipe take-off from the main supply manifold. Thus, the two lines which take-off from the supply manifold are split into four individually controllable lines which then lead to the spray

nozzle headers.

The rotometers for these two sources are Fisher-Porter Models 2235573 0.7 - 3.6 liters per minute (.2-2 gpm) and 2235621 3.8 - 41.6 liters per minute (1-11 gpm) Ratosights for spray towers #1 and #2 respectively.

The main water control board is also equipped with necessary fittings and valves to accommodate reuse of the drain water from spray tower #2 into spray tower #1. This recycle system has not yet been put into service, however.

10. Water Drain System

Water is currently used on a once through basis in the pilot plant although a partial recycle system will be employed in future studies. Individual drains leading through the trailer floor serve the cooling tower, both corona collection plate flushing systems, both water spray towers and the outlet test duct cleaning system. Water used to clean the inlet test duct runs into the drain serving corona #1 and water collected in the demister exits through the #1 spray tower drain. All drains are equipped with water legs (locks) to insure that no air leakage into the system occurs.

B. DESCRIPTION OF SOURCE TEST EQUIPMENT

1. General

The following table indicates the source test equipment used to measure various parameters. Further information concerning charge to mass measurements and the UW Cascade Impactor is given below.

2. UW Mark III Cascade Impactor

A UW Mark III Cascade Impactor was used to measure both particle size distribution and mass concentration at both the inlet and outlet test ducts. The impactor provides this information by segregating the aerosol sample into eight discrete size intervals (seven collection plates plus one final filter). The aerosol weight on each state provides size distribution information and the total weight is used to determine the mass concentration. The basic components of a sampling train utilizing a UW Mark III Cascade Impactor are shown schematically in Figure 7. The impingers are used to collect water vapor in the sample air stream and provide a basis for calculating the moisture content of the gas

Table 2. SOURCE TEST PARAMETERS AND MEASUREMENT TECHNIQUES

Parameter	Equipment
1. Air	
a. velocity and volume	S-type pilot tube with draft gage
b. temperature	thermometer
c. moisture	wet and dry bulb thermometer and checked by volume of condensate
d. atmospheric pressure	barometer
e. static pressure	Magnehelic gage
2. Water Spray Towers	
a. water flow	rotometers
b. water charge to mass	digital multimeter
3. Aerosol	
a. mass concentration	UW Mark III Cascade Impactor
b. size distribution	UW Mark III Cascade Impactor
c. aerosol charge to mass	digital multimeter

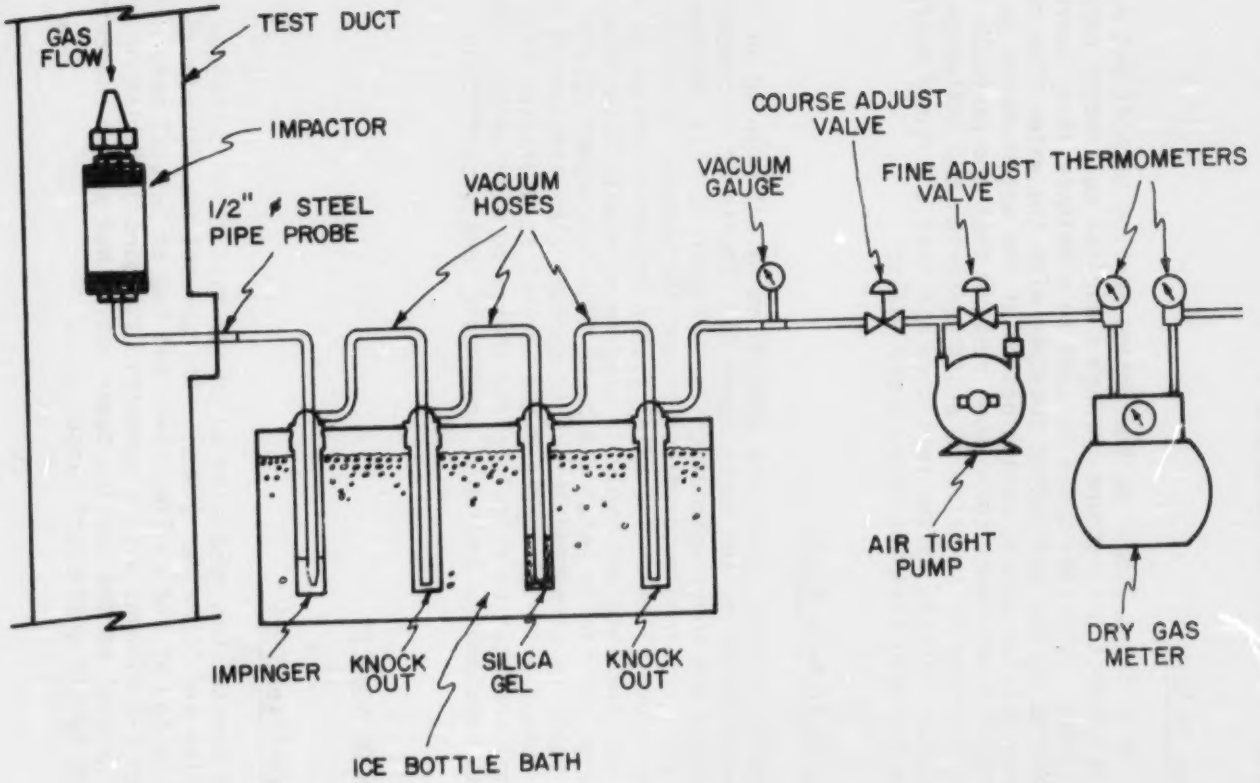

FIGURE 7. UW CASCADE IMPACTOR SAMPLING TRAIN

stream which may be checked against the wet bulb - dry bulb determination. The dry gas meter is used to determine isokinetic sampling conditions as well as the total sample volume.

By conducting simultaneous particle size distribution tests at both the inlet and outlet test ducts, the size dependent collection efficiency curve of the pilot plant may be measured.

3. Water Charge to Mass

The metal water traps (legs) on the drains serving both #1 and #2 spray towers are connected to ground through a digital multimeter capable of reading milliamps. Shielded cable is used to eliminate stray current. The current measured by the multimeter together with the water flow rate through the spray nozzles permit determination of the water charge to mass ratio. Proper measurement techniques require that the particle charging corona sections be inactive to avoid measuring the influence of the negative charges carried by the particles and that all spray nozzles be electrically isolated from the spray tower walls.

4. Aerosol Charge to Mass Ratio

Aerosol charge to mass ratios are determined by withdrawing an aerosol sample between corona #1 and spray tower #1. The basic components of this sampling train are shown schematically in Figure 8. The impinger is used to remove any entrained water droplets and the aerosol is collected on a 47 mm glass fiber filter. The metal filter holder is housed in a grounded metal box and shielded cable is used to eliminate interference from external electric fields which can cause high background current readings. The cable is connected to ground through a multimeter capable of measuring nanoamps. The current and the aerosol accumulation rate (weight per time) are used to calculate the charge to mass ratio. The dry gas meter is required to determine isokinetic sample conditions.

C. DESCRIPTION OF SOURCES

1. Dioctyl Phthalate (DOP)

A DOP test aerosol was generated by an air aspiration technique described by Parrish and Schneider (1968). The aerosol was introduced directly into the top of the cooling tower and had an initial mass mean diameter between 1-2 microns with a geometric standard deviation of about 2.75. The DOP aerosol at the cooling tower outlet had a mass concentration in the .008 to .14 grains/acf range.

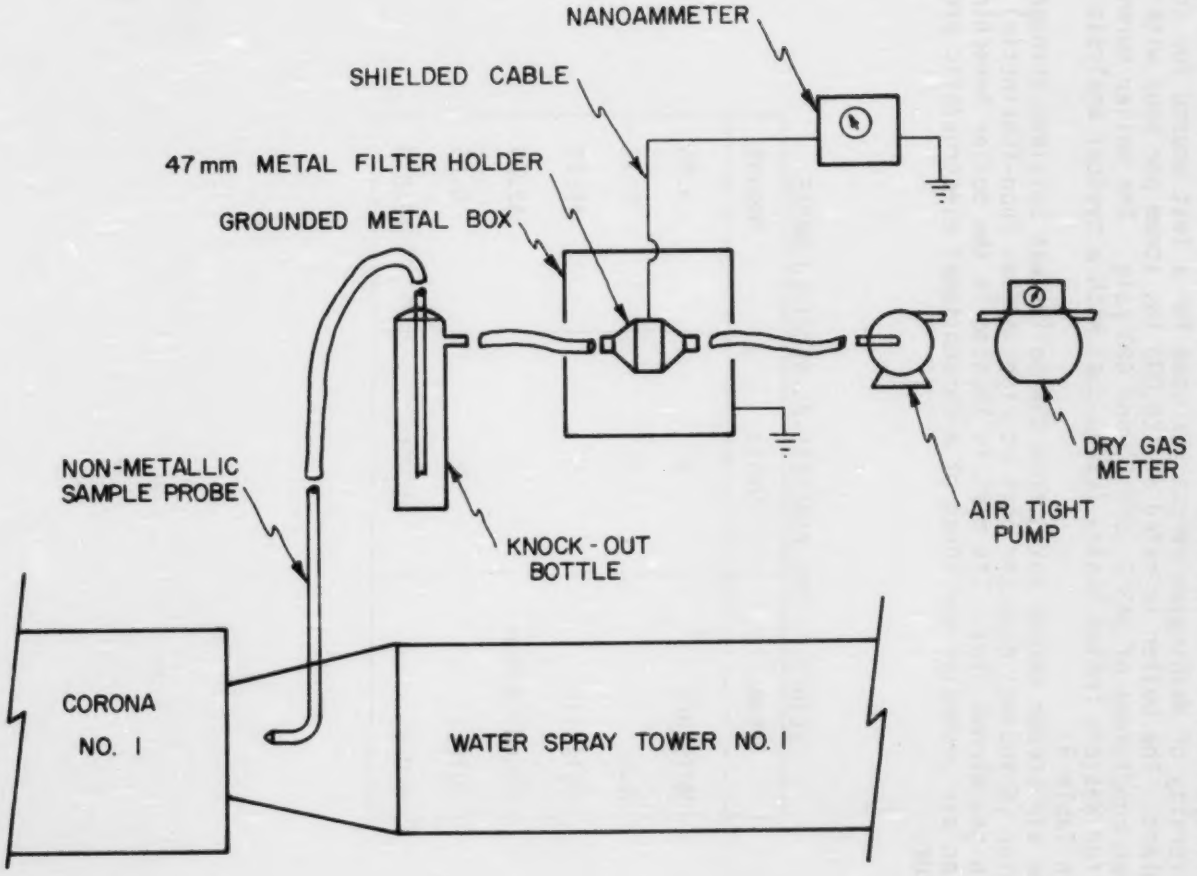

FIGURE 8. SAMPLING TRAIN FOR AEROSOL CHARGE TO MASS

2. Pulverized Coal Fired Boiler

A Riley Stoker Corporation pulverized coal fired boiler operating on the University of Washington campus was used for a test source for the pilot plant. The boiler is rated at 120,000 lbs steam per hour with outlet steam conditions of 343°C (650°F) and 400 psig. The boiler burns a low sulfur Western United States (Utah) coal with a typical analysis as given in Table 3.

The air stream sample taken from the boiler was obtained through a 0.15 meter (6 inches) diameter port at right angles (non-isokinetic) to the main gas stream flow. The port is located in the boiler breeching behind an air preheater and ahead of a conventional electrostatic precipitator.

Table 3. COAL ANALYSIS-AS RECEIVED BASIS

Item	Units	Amount
Moisture	%	6.66
Ash	%	5.12
Volatile	%	45.73
Fixed Carbon	%	42.49
Sulfur	%	0.65
H.H.V.	Btu/lb	12,819

SECTION V

RESULTS

A. TEST CONDITIONS

1. Dioctyle Phthalate (DOP)

Eight simultaneous inlet and outlet tests were conducted using the DOP aerosol. A detailed itemization of the test conditions is presented in Tables 6 through 13 which are located in Appendix A. The items specified in these tables include the air flow volume and temperature at the outlet test duct, the volume of water sprayed into towers #1 and #2, the conditions of the three power supplies (kV and mA), the inlet and outlet test duct aerosol characteristics (mass mean diameter, standard geometric deviation and concentration) and the collection efficiency figured on a mass basis. As an aid to discussing the DOP test results, however, Table 4 summarizes the conditions of the eight tests.

Tests number 1 through 6 were all conducted with the aerosol and water droplets charged to opposite polarity. The air flow through the pilot plant, which is inversely related to the gas residence time, varied from a low of 569 m^3/hr (335 acfm) in test number 3 to a high of about 1,700 m^3/hr (1,000 acfm) in test number 6. The water to gas ratio (gal/1,000 acf) ranged from a low of 6.36 in test number 6 to a high of 13.43 in test number 3. Particle charging voltage in the corona sections was maintained at 70 kV in all of the first six tests while the voltage maintained on the spray tower nozzles was either 15 or 25 kV.

Test number 7 employed uncharged aerosol and droplets while test 8 employed uncharged aerosol and charged droplets. Test number 7 corresponds to operating the pilot plant as a conventional spray tower.

2. Coal Fired Boiler

Three simultaneous tests were conducted on emissions from the University of Washington pulverized coal fired boiler. The conditions during the test are presented in Tables 16, 17 and 18 located in Appendix

Table 4. SUMMARY OF DOP TEST CONDITIONS

Test No.	Gas Flow at Outlet Test Duct (acfm)	Water to Gas Ratio (gal/1,000 acf)	Voltages (kV)		Comments
			Coronas	Spray	
1	774	5.81	70	25	Notes 1 & 2
2	533	8.44	70	25	Notes 1 & 2
3	335	13.43	70	25	Notes 1 & 2
4	515	8.90	70	25	Note 1
5	480	12.71	70	15	Note 1
6	959	6.36	70	25	Note 1
7	968	6.20	0	0	Aerosol & water uncharged. System operating as a spray chamber
8	970	6.18	0	15	Aerosol uncharged & water uncharged

Note 1: Aerosol & water charged
Note 2: Corona #1 & spray tower #1 inactive

B while a summary of the test conditions is presented in the following table.

Table 5. SUMMARY OF COAL FIRED BOILER TEST CONDITIONS

Test No.	Gas Flow at Outlet Test Duct (acfm)	Water to Gas Ratio (gal/1,000 acf)	Voltages (kV)	
			Coronas	Spray
1	997	5.82	65	20
2	974	5.72	65	15
3	1,060	2.36	65	20

The boiler was baseloaded at about 67% of rated capacity during the three tests and sootblowing was encountered during the second test.

B. PARTICLE COLLECTION EFFICIENCY

1. Dioctyl Phthalate

Figures 9 through 16 show the collection efficiency of the pilot plant as a function of particle size. Included in these figures are some of the operating condition parameters which are present in Table 4 plus the overall particle collection calculated on a mass basis.

The collection efficiency for a 0.5 micron diameter particle ranged from a high of 99.8% in test number 3 to a low of 10.0% in test number 8. These same two tests had an overall mass basis collection efficiency of 99.68% and 24.98% respectively.

When operating the pilot plant at the nominal air flow of about 1,700 m^3/hr (1,000 cfm) with both aerosol and water droplets charged and with a water to gas ratio of about 6 gal/1,000 acf, the collection efficiency of a 0.5 micron diameter particle was about 90% while the overall mass basis collection efficiency was 89.00% (see Figure 14, test number 6).

2. Coal Fired Boiler

Figure 17, 18 and 19 present the particle collection efficiency of

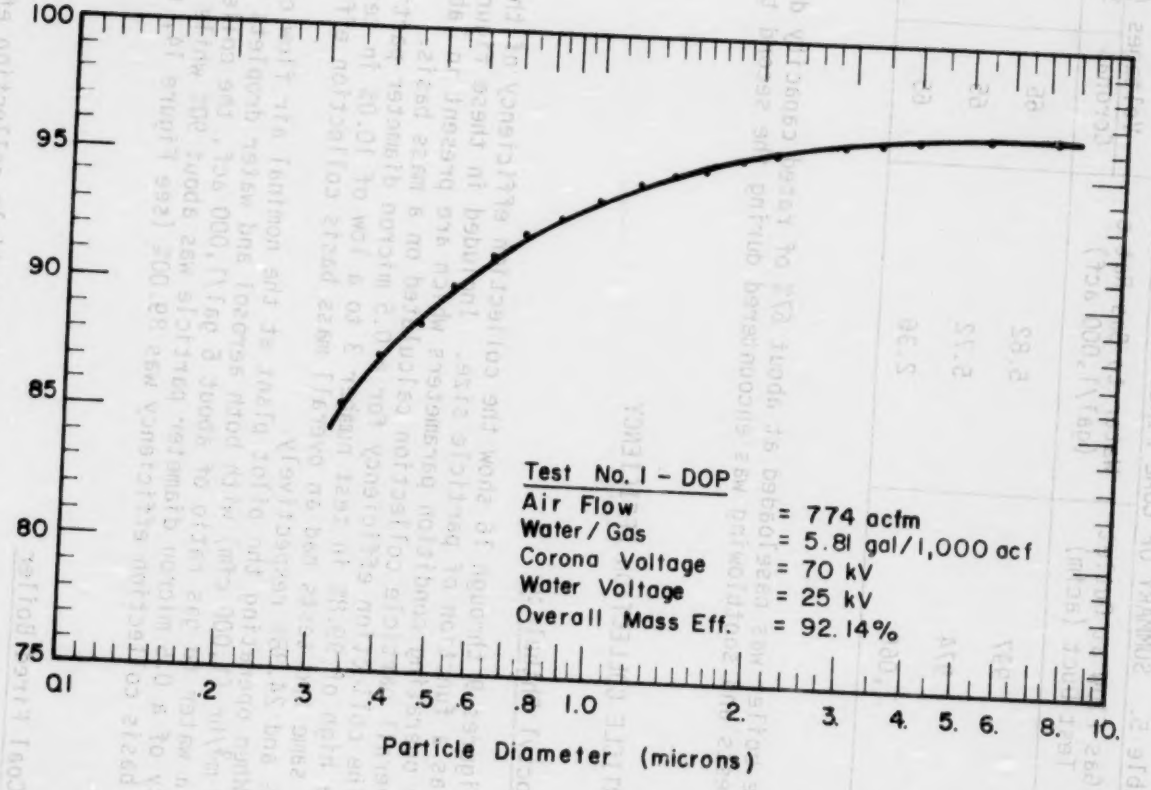

Figure 9. Collection efficiency vs. particle size for DOP test No. 1

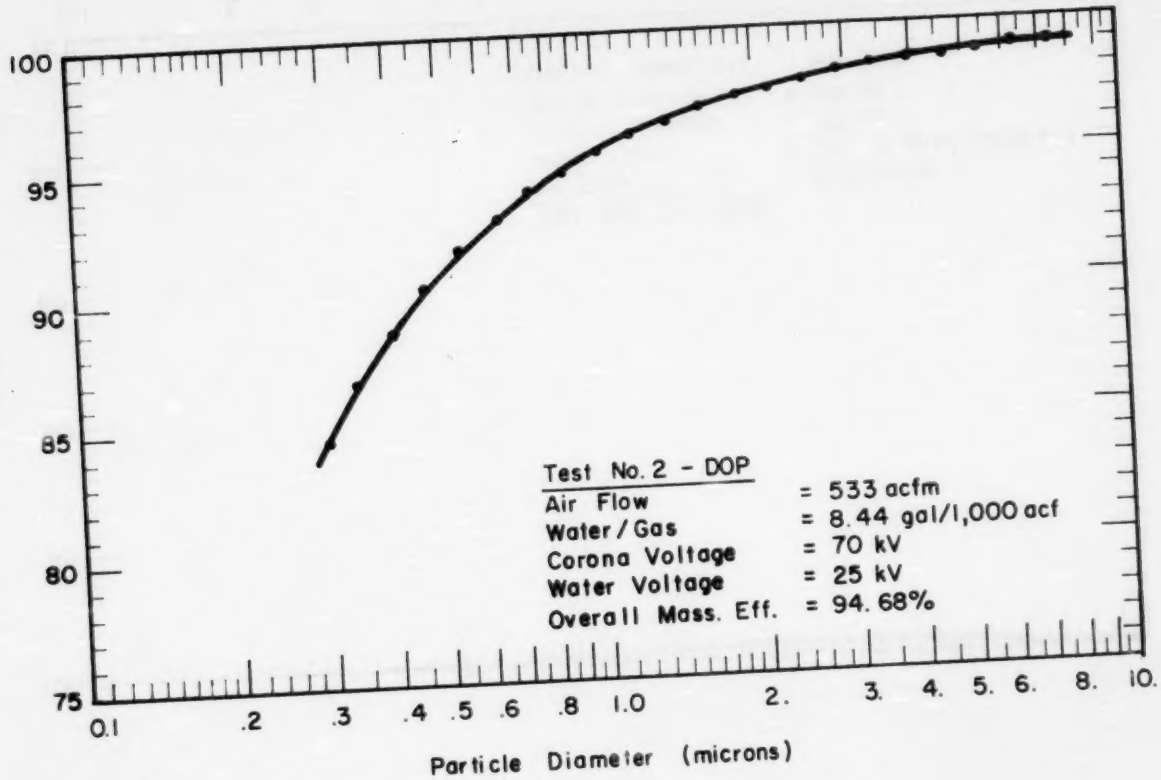

Figure 10. Collection efficiency vs. particle size for DOP test No. 2

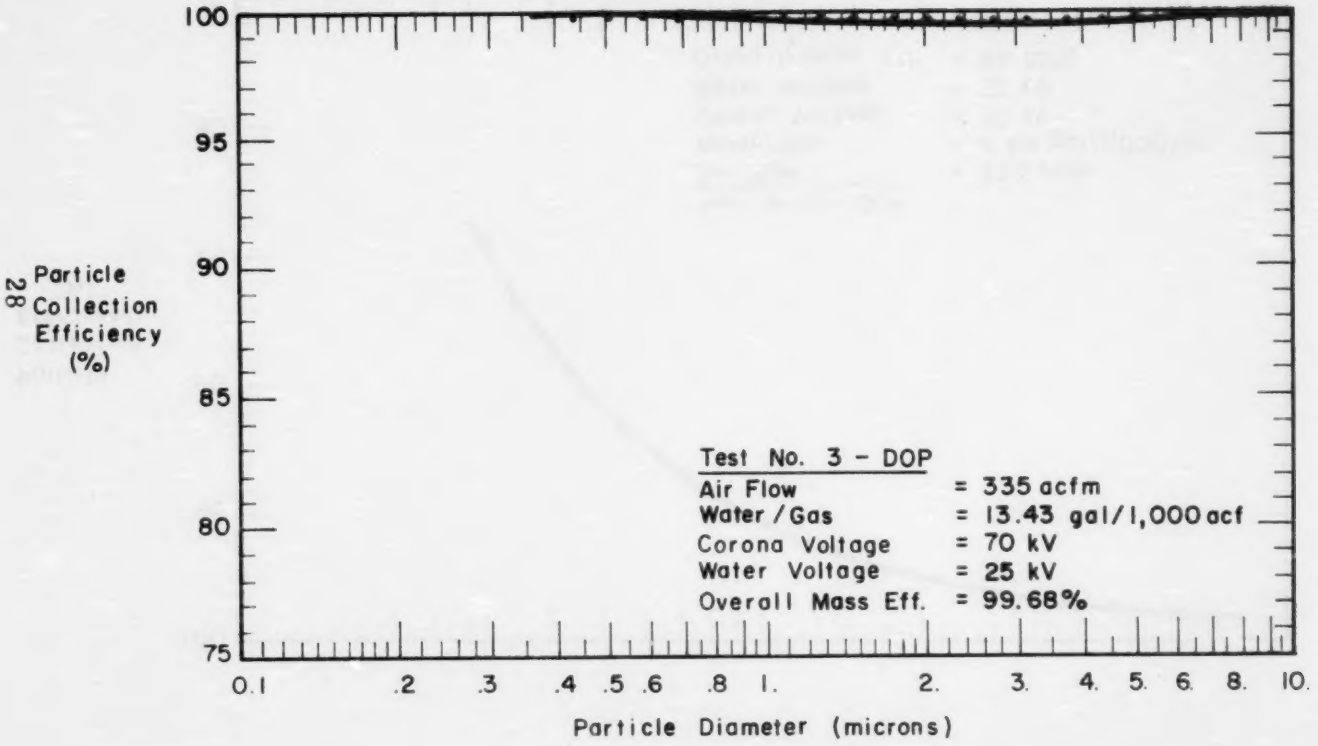

Figure 11. Collection efficiency vs. particle size for DOP test No. 3

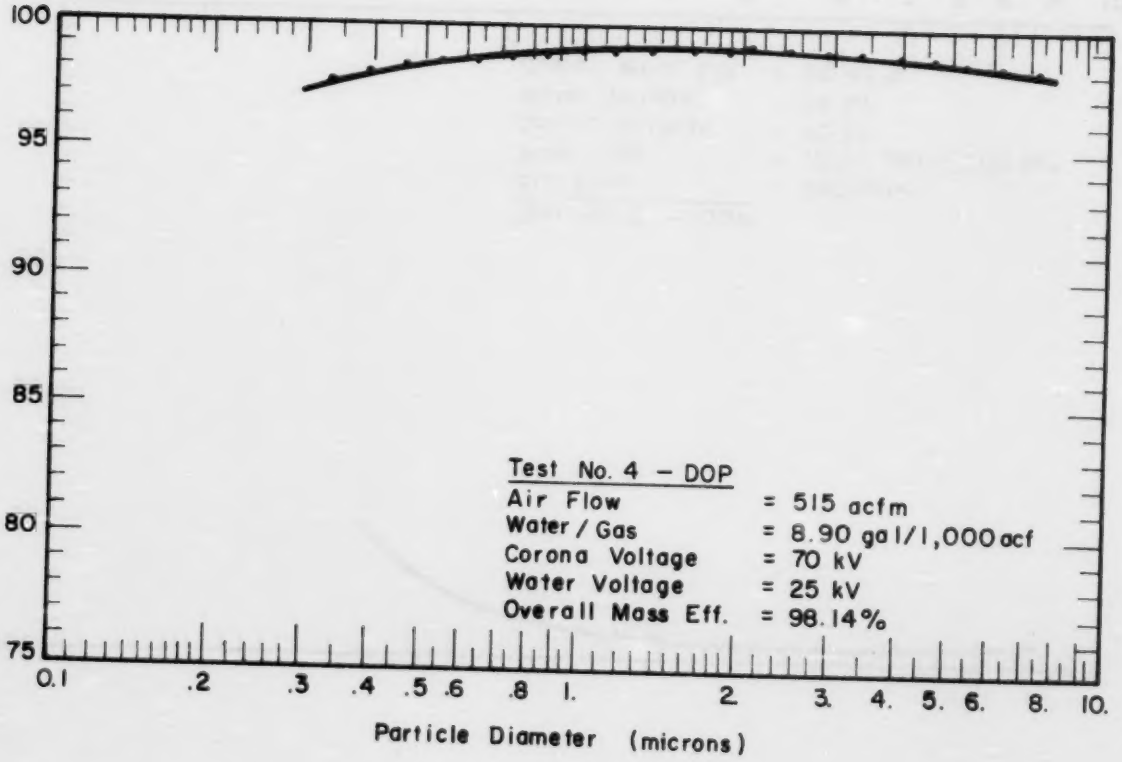

Figure 12. Collection efficiency vs. particle size for DOP test No. 4

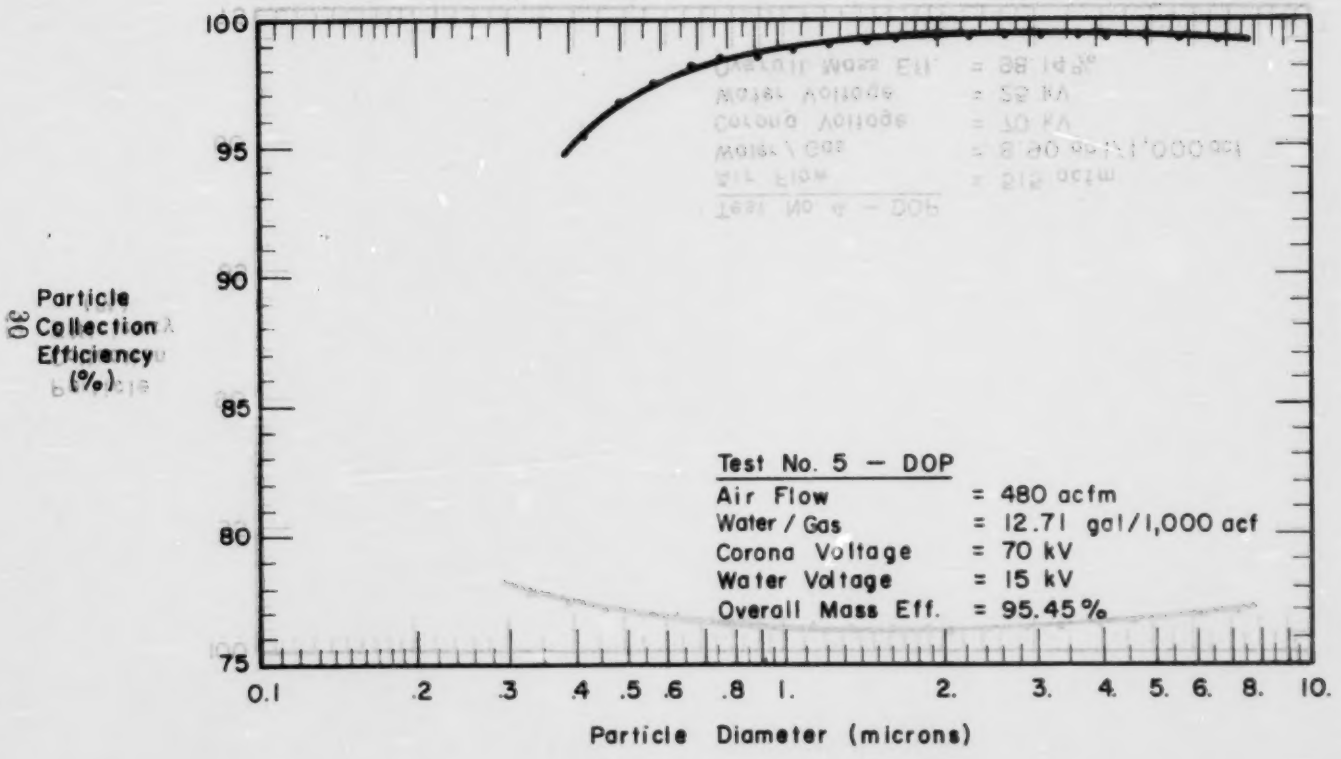

Figure 13. Collection efficiency vs. particle size for DOP test No. 5

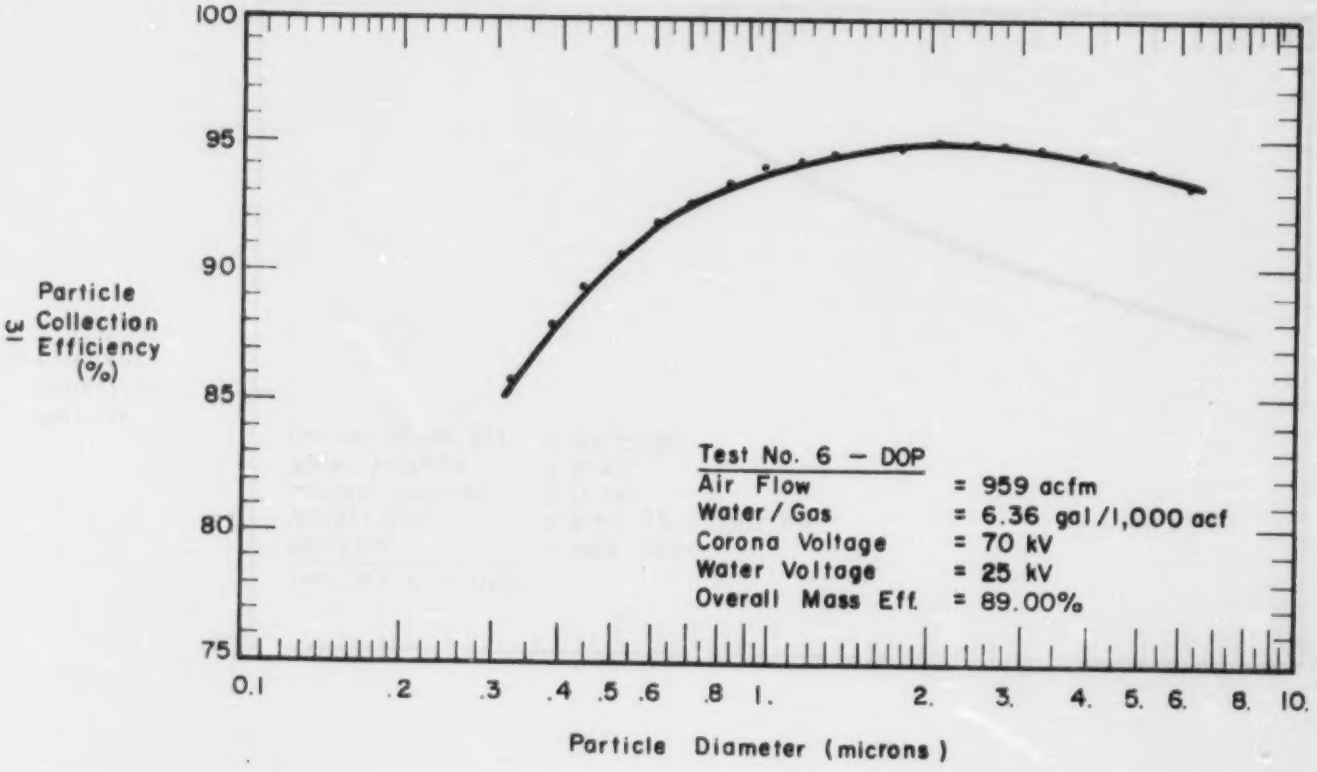

Figure 14. Collection efficiency vs. particle size for DOP test No. 6

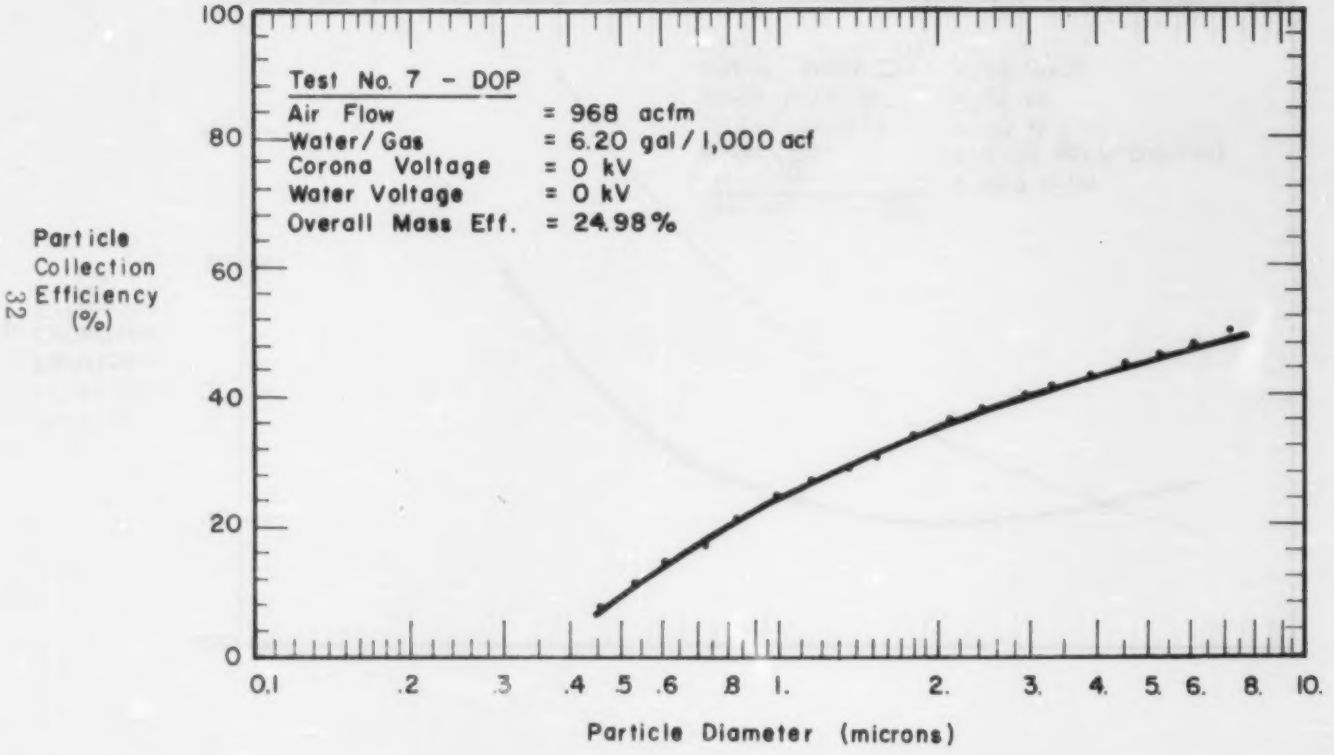

Figure 15. Collection efficiency vs. particle size for DOP test No. 7

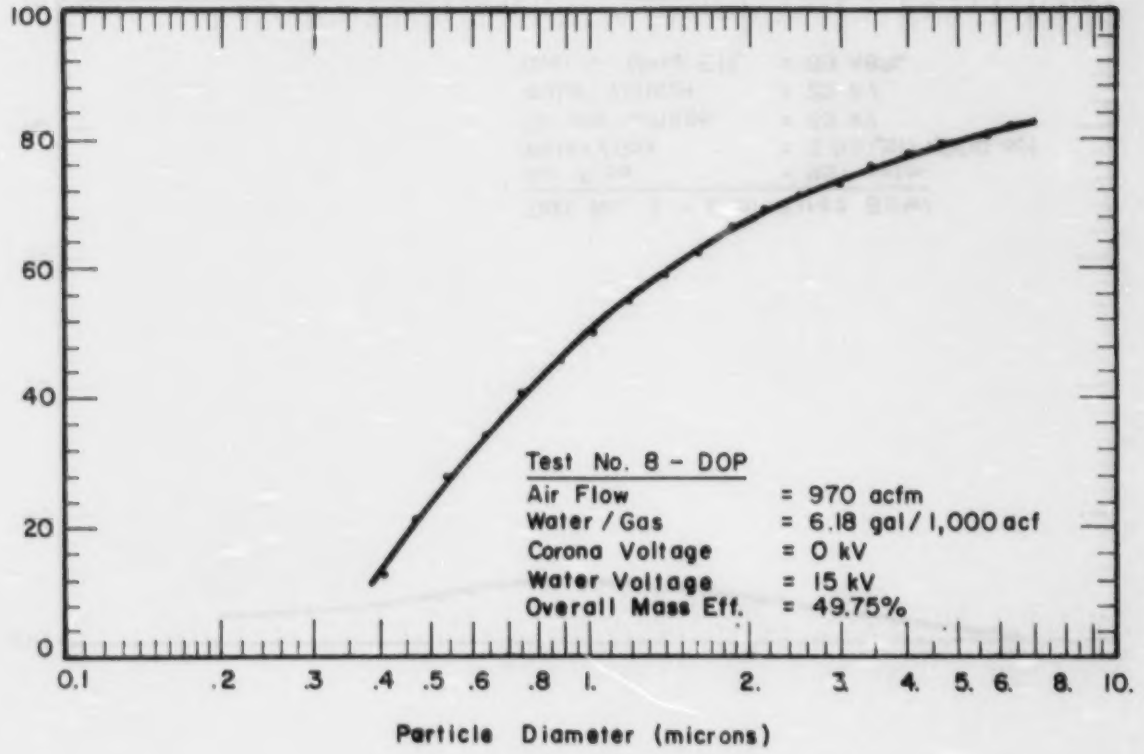

Figure 16. Collection efficiency vs. particle size for DOP test No. 8

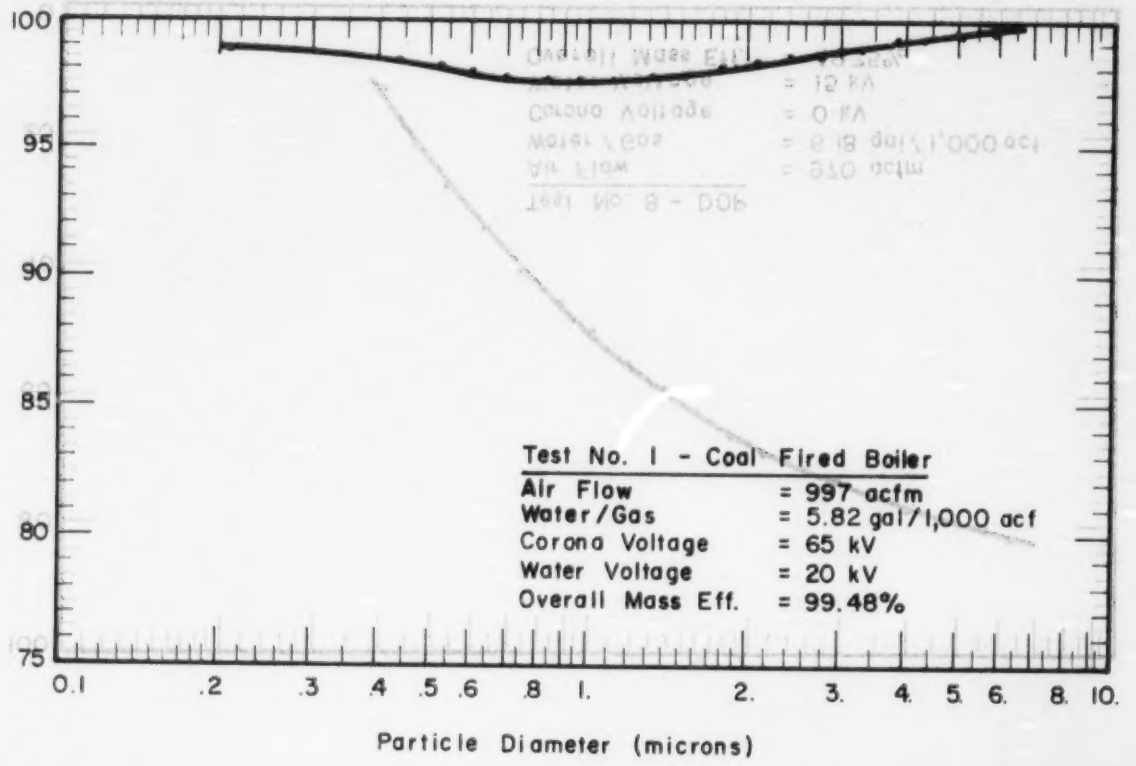

Figure 17. Collection efficiency vs. particle size for coal fired boiler test No. 1.

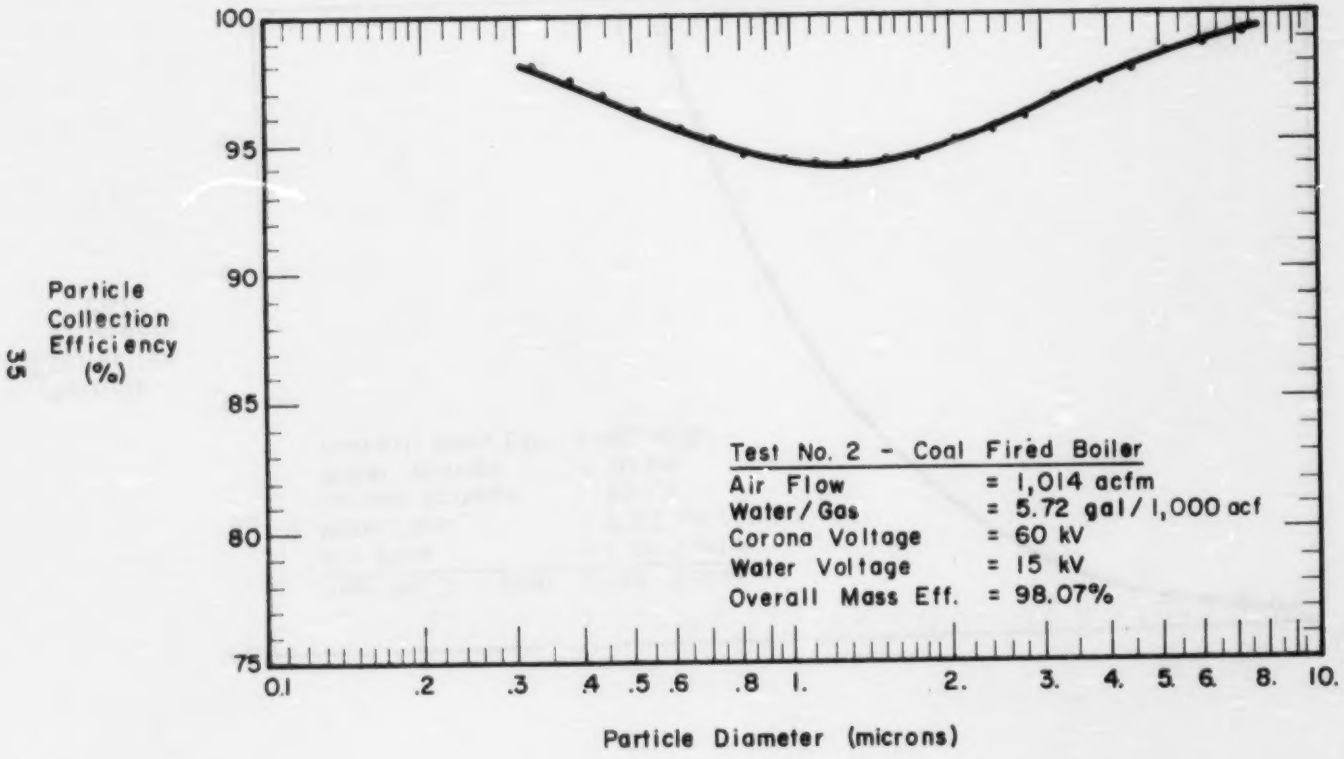

Figure 18. Collection efficiency vs. particle size for coal fired boiler test No. 2

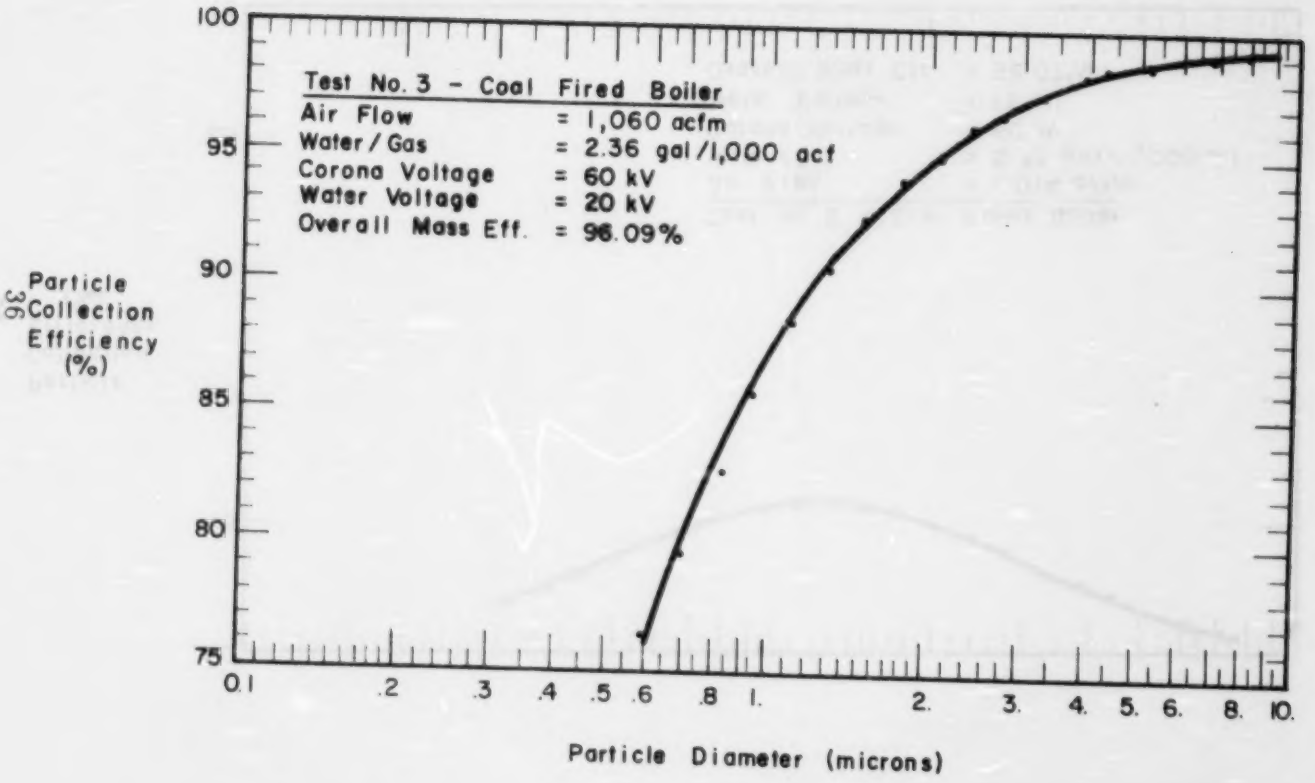

Figure 19. Collection efficiency vs. particle size for coal fired boiler test No. 3

the pilot plant as a function of particle size. The overall mass basis particle collection efficiency plus some pilot plant operating conditions are also noted on these three figures.

The collection efficiency of a 0.5 micron diameter particle ranged from a high of 98.0% in test number 1 to a low of 47.0% in test number 3. These same two tests had overall mass basis particle collection efficiencies of 99.48% and 96.09% for tests 1 and 3, respectively.

SECTION VI

DISCUSSION OF RESULTS

A. DIOCTYL PHTHALATE (DOP)

1. Influences of Gas Residence Time

The particle collection efficiency is directly related to the gas residence time such that an increase in gas residence time provides an increase in particle collection efficiency at any given particle size. For example, test 4 used both spray towers and had a 37% longer gas residence time than test 2 which used only one spray tower. Accordingly, test 4 had a collection efficiency for a 0.5 micron diameter particle of 98.5% compared to 91.5% for test 2. The corresponding overall mass basis collection efficiency increased from 94.68% to 98.14%.

The size dependent collection efficiency curves for these two tests have been plotted on one graph and are presented in Figure 20. This figure shows that the particle collection efficiency becomes independent (i.e., is unchanged) of gas residence time for particle diameters greater than about 4-6 microns.

2. Influence of Water to Gas Ratio and Applied Nozzle Voltage

Particle collection efficiency increases with both increasing water to gas ratios and increasing voltage applied on the water spray nozzles. Thus, the size dependent particle collection efficiency curve can be maintained by an increase in the water droplet charging voltage and a decrease in the water to gas ratio. This may be seen in a comparison of test 4 (8.90 gal/1,000 acf and 25 kV droplet charging voltage) and test 5 (12.71 gal/1,000 acf and 15 kV droplet charging voltage). The particle collection efficiency curves for these two tests are presented in Figure 21 which shows that the difference in particle collection efficiency is only 1.6% at 0.5 micron diameter, 0.2% at 0.75 microns diameter and 0.1% at 1.0 and 2.0 micron diameters.

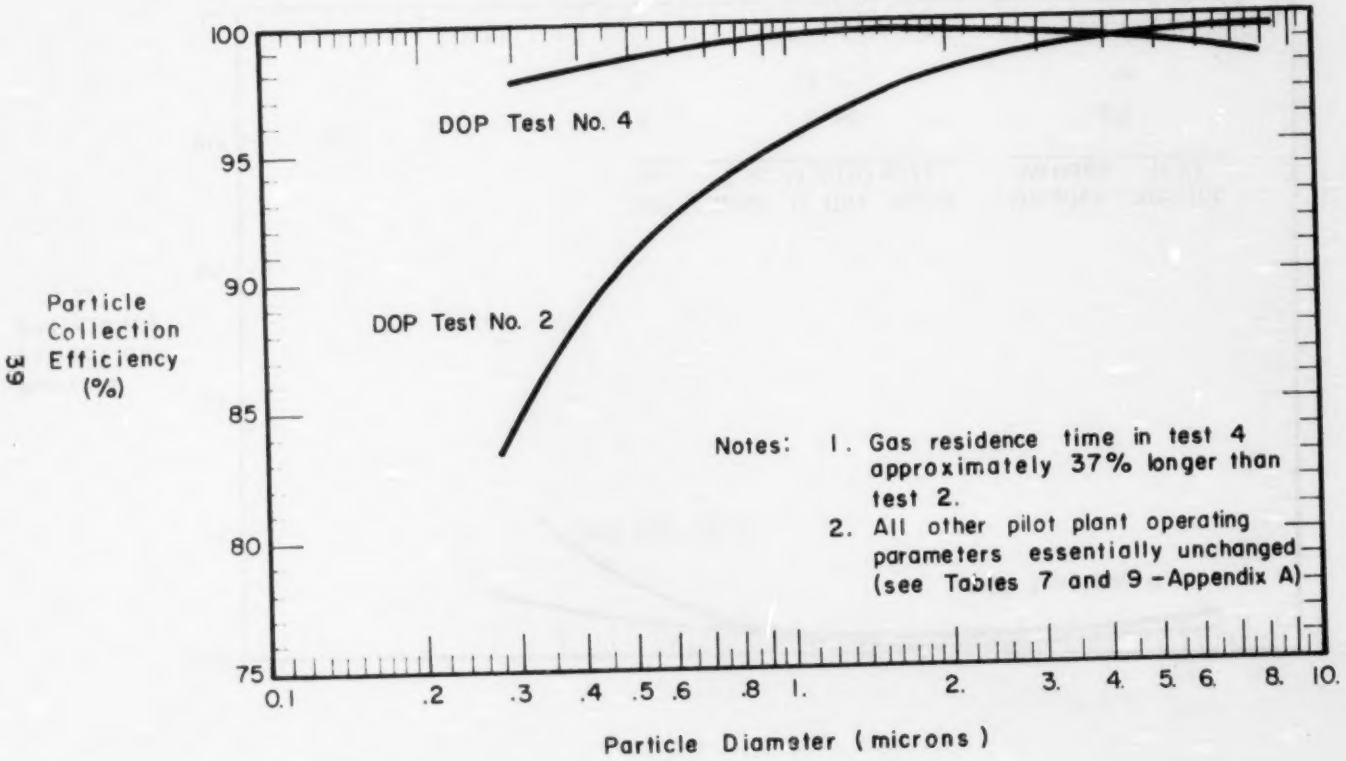

Figure 20. Influence of gas residence time on particle collection efficiency

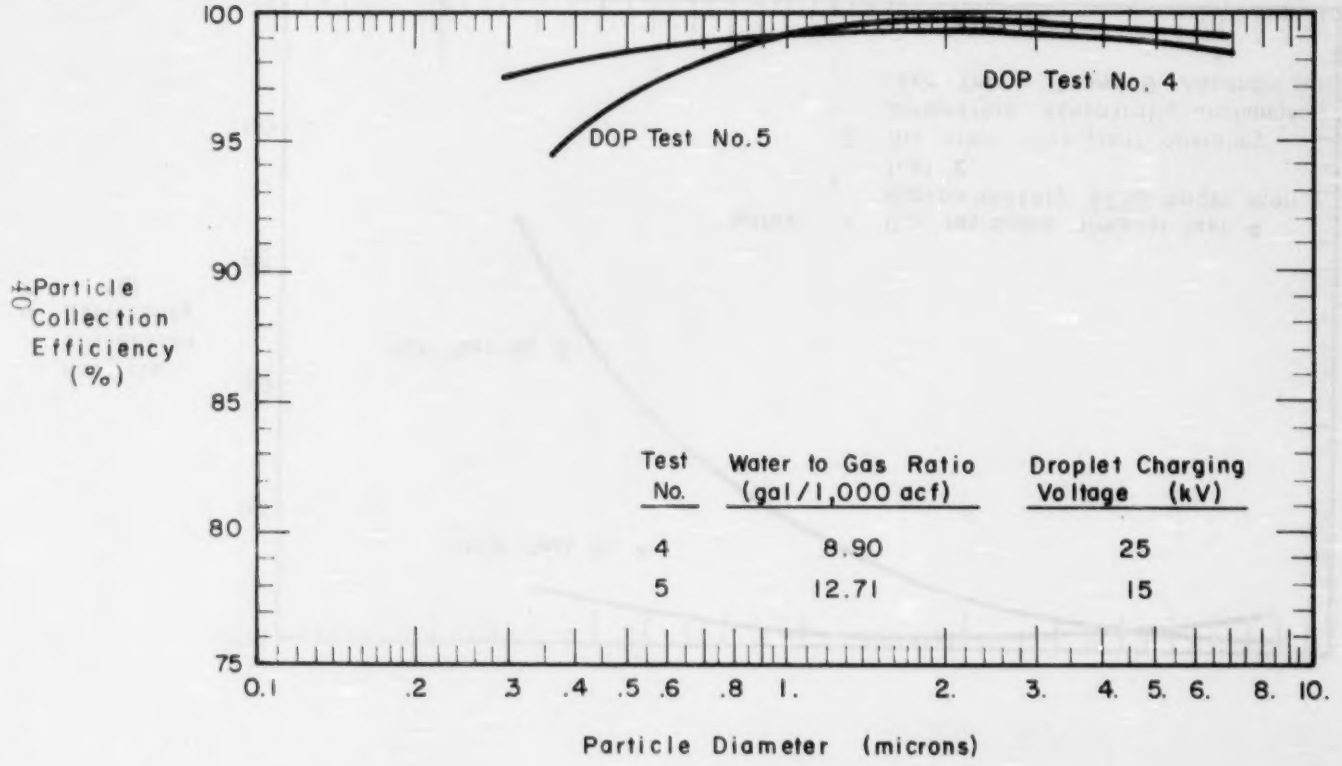

Figure 21. Influence of water to gas ratio and water droplet charging voltage on particle collection efficiency.

3. Influence of Aerosol and Droplet Charging

Particle collection efficiency at any given size increases when either the particles or water droplets change from an uncharged to a charged condition. For example, test 7 utilized uncharged particles with uncharged droplets (conventional spray tower), test 8 utilized uncharged particles with charged droplets, and test 6 utilized charged particles with charged droplets. The size dependent particle collection efficiency curves for these three tests have been combined in Figure 22 which shows that the collection efficiency for a 0.5 micron diameter particle increases from 10.0% in test 7 (both uncharged) to 23.5% in test 8 (particles uncharged and droplets charged) to 91.5% in test 6 (both charged). The corresponding overall mass basis particle collection efficiencies increased from 24.98% to 49.75% to 89.00%.

B. COAL FIRED BOILER

1. Influence of Applied Nozzle Voltage

Particle collection efficiency at any given particle size increases as the water droplet charging voltage is increased. For example, test 2 (15 kV droplet charging voltage) had a 96.5% collection efficiency for a 0.5 micron diameter particle while test 1 (20 kV droplet charging voltage) had a corresponding 99.1% collection efficiency. Collection efficiency at other particle sizes may be seen in Figure 23 which presents the efficiency curves for these two tests. The overall mass basis collection efficiency was 98.07% and 99.48% for tests 2 and 1, respectively.

2. Influence of Water to Gas Ratio

Particle collection efficiency is directly related to the water to gas ratio (gal/1,000 acf) such that an increase in water to gas ratio provides an increase in the particle collection efficiency at any given particle size. For example, test 3 (2.36 gal/1,000 acf) and a 76.0% collection efficiency at 0.6 micron diameter while the corresponding efficiency for test 1 (5.82 gal/1,000 acf) was 97.8%. The particle size dependent collection efficiency curves for these two tests are presented in Figure 24. The overall mass basis particle collection efficiency increased from 96.09% to 99.48% for test 3 and 1, respectively. This relatively small increase in overall efficiency is due to the fact that the mass mean diameter of the coal fired boiler particles at the inlet test duct is quite large (averages about 7.25 microns).

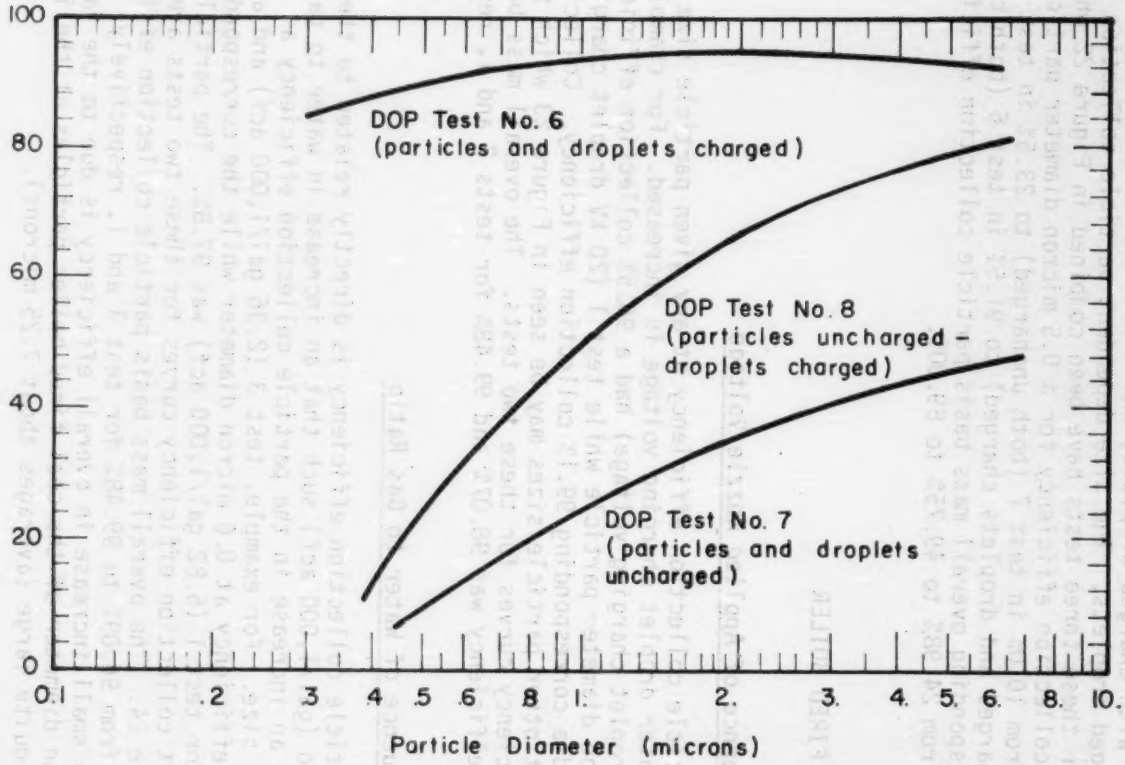

Figure 22. Influence of aerosal and droplet charging on particle collection efficiency.

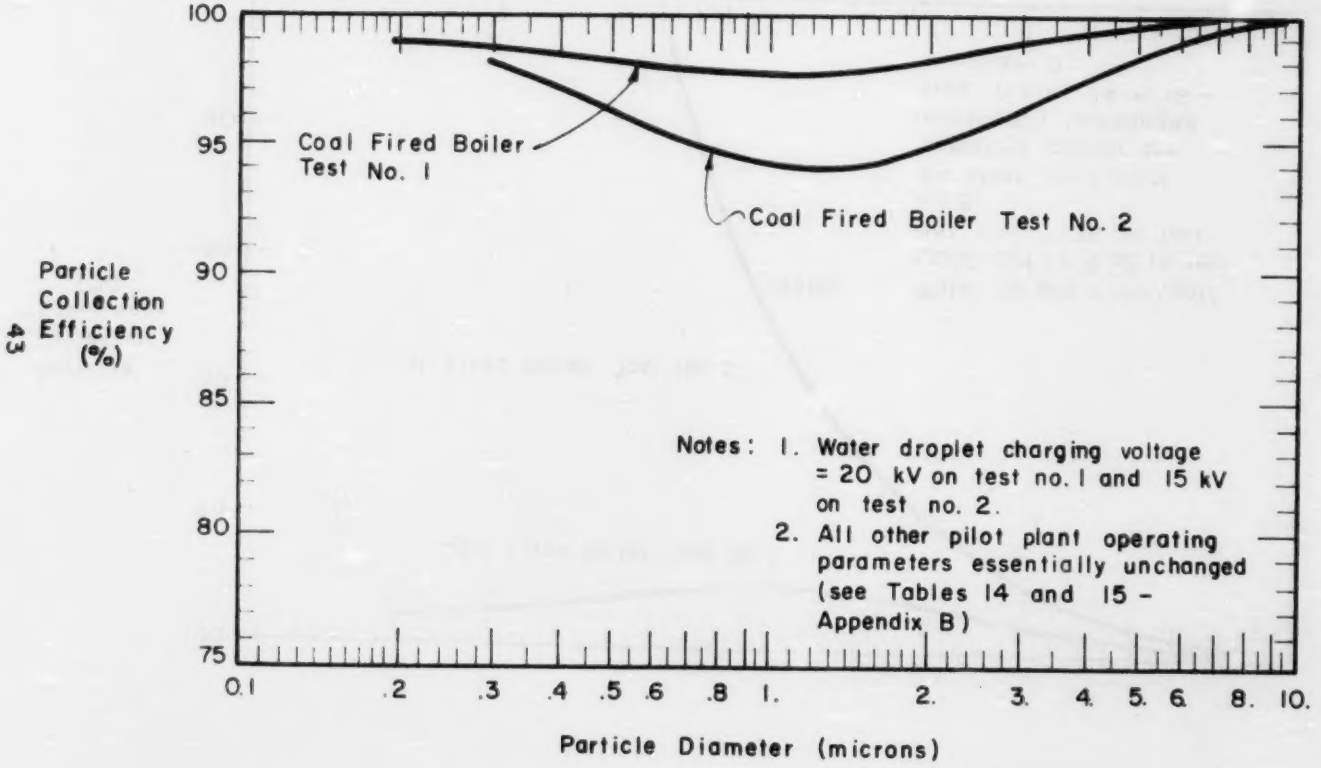

Figure 23. Influence of water droplet charging voltage on particle collection efficiency.

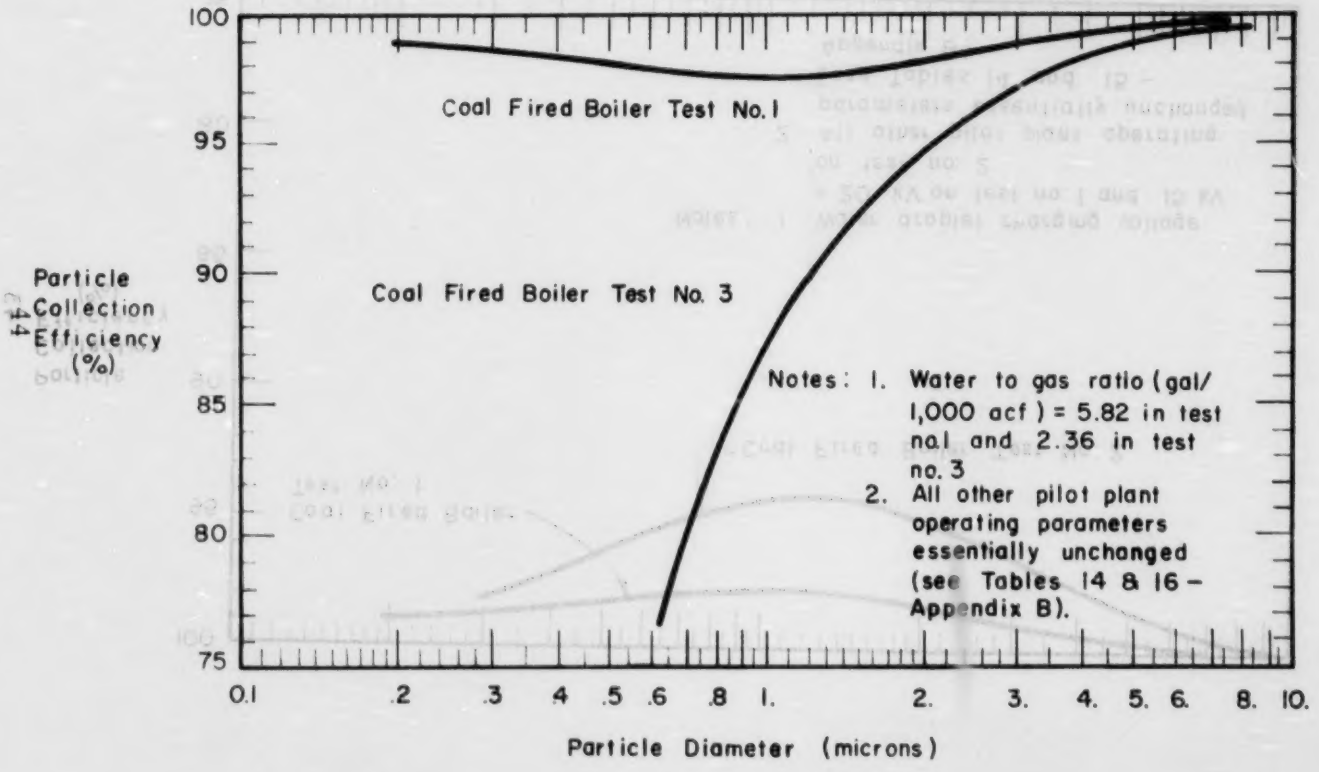

Figure 24. Influence of water to gas ratio on particle collection efficiency.

C. ERROR ANALYSIS

The development of an expression for the maximum error in the size dependent collection efficiency curve is presented in Appendix C. This expression was used to calculate the error bands for DOP test 7 (particles and droplets uncharged), 8 (particles uncharged and droplets charged) and 6 (particles and droplets charged). A summary of the calculations are also presented in Appendix C (Tables 17-19).

Figure 25 shows the size dependent particle collection efficiency curves from these three tests together with their respective error bands. All three tests had a maximum error due to weighing uncertainties of about ±4% for particle sizes less than about 2 microns diameter. The uncertainty increased at larger particle sizes due to the fact that size distribution of the test sample was relatively small (average mass mean diameter = 1.32 microns).

Figure 25 also shows that the error bands do not overlap for particle diameters less than 4.5 microns and, thus, the differences in the efficiency curves result from differences in the pilot plant operating conditions (e.g., particle and droplet charging) and not from uncertainties introduced by weighing errors.

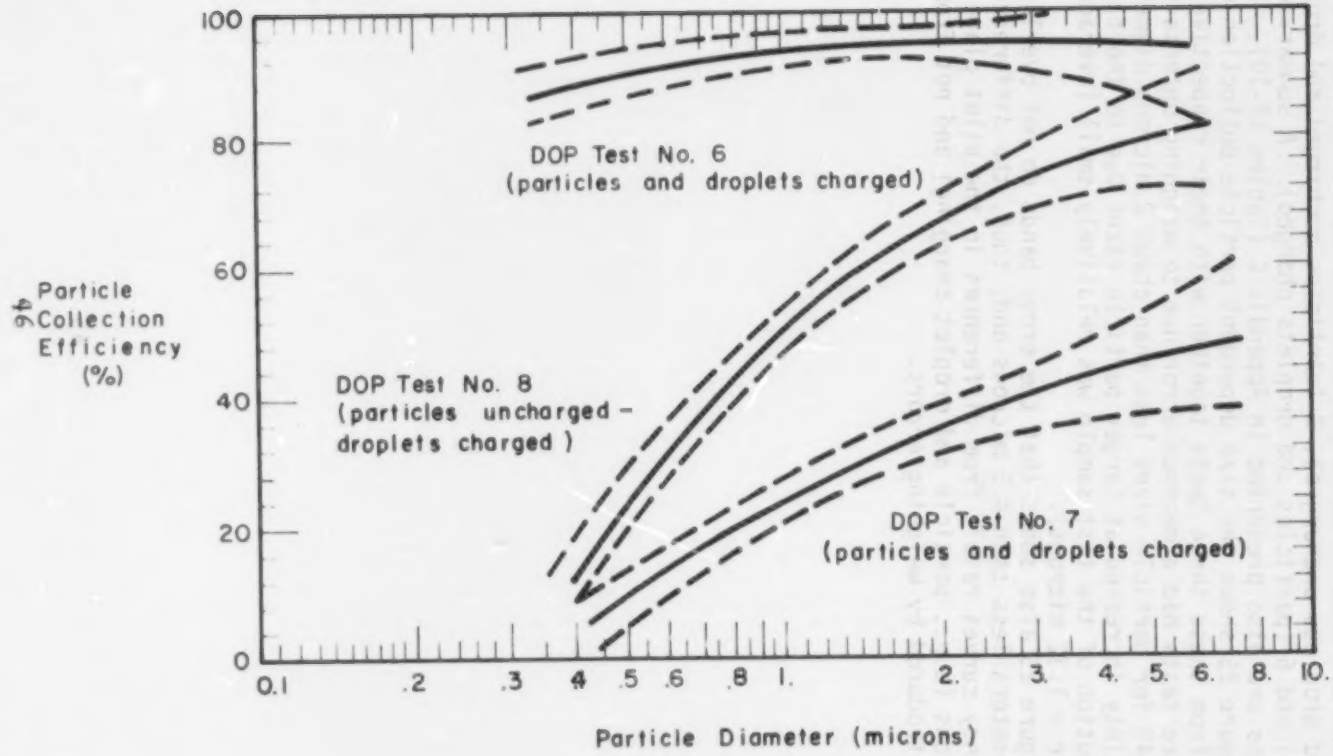

Figure 25. Error bands in the size dependent particle collection efficiency curves.

SECTION VII

REFERENCES

1. Bevington, P. R., Data Reduction and Error for the Physical Sciences, McGraw-Hill, New York, (1969).

2. Oglesby, S., Jr., A Manual of Electrostatic Precipitation Technology, Report Number APTD-0610, Prepared for The National Air Pollution Control Administration (1970).

3. Parrish, E. C. and Schneider, R. W., Review of Inspection and Testing of Installed High-Efficiency Particulate Air Filters at ORNL, Presented at the Symposium On Operating and Developmental Experience in the Treatment of Airborne Radioactive Wastes, Sponsored by the International Atomic Energy Agency, (1968).

APPENDIX A

Table 6. DOP TEST NO. 1 PARAMETERS

Item	Units	Amount
A. Gas at Outlet Test Duct		
1. temperature	°C (°F)	18.0 (64.4)
2. volume	m^3/hr (acfm)	455 (774)
B. Water		
1. water to gas ratio	gal/1,000 acf	5.81
2. charge per mass	10^{-6}coul/gm	n.a.
C. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	70
b. current	mA	0.8
2. water spray tower sections		
a. voltage	kV	25
b. current	mA	2.0
3. demister		
a. voltage	kV	50
b. current	mA	0.2
D. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	1.53
b. geometric standard deviation	-	2.95
c. concentration	gr/sdcf	0.0084
2. outlet test duct		
a. mass mean diameter	microns	0.64
b. geometric standard deviation	-	3.83
c. concentration	gr/sdcf	0.0007
E. Collection Efficiency		
1. mass basis	%	92.14
2. size dependent	See Figure 9	

Note: 1) Corona #1 and spray tower #1 inactive.

Table 7. DOP TEST NO. 2 PARAMETERS

Item	Units	Amount
A. Gas at Outlet Test Duct		
1. temperature	°C (°F)	21.0 (69.8)
2. volume	m^3/hr (acfm)	906 (533)
B. Water		
1. water to gas ratio	gal/1,000 acf	8.44
2. charge per mass	10^{-6}coul/gm	n.a.
C. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	70
b. current	mA	0.6
2. water spray tower sections		
a. voltage	kV	25
b. current	mA	1.7
3. demister		
a. voltage	kV	50
b. current	mA	0.1
D. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	1.39
b. geometric standard deviation	-	2.75
c. concentration	gr/sdcf	0.0327
2. outlet test duct		
a. mass mean diameter	microns	0.50
b. geometric standard deviation	-	2.96
c. concentration	gr/sdcf	0.0019
E. Collection Efficiency		
1. mass basis	%	94.68
2. size dependent	See Figure 10	

Note: 1) Corona #1 and spray tower #1 inactive.

Table 8. DOP TEST NO. 3 PARAMETERS

Item	Units	Amount
A. Gas at Outlet Test Duct		
1. temperature	°C (°F)	18.0 (64.4)
2. volume	m^3/hr (acfm)	569 (335)
B. Water		
1. water to gas ratio	gal/1,000 acf	13.43
2. charge per mass	10^{-6}coul/gm	n.a.
C. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	70
b. current	mA	0.5
2. water spray tower sections		
a. voltage	kV	25
b. current	mA	2.7
3. demister		
a. voltage	kV	51
b. current	mA	0.1
D. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	1.51
b. geometric standard deviation	-	2.74
c. concentration	gr/sdcf	0.0155
2. outlet test duct		
a. mass mean diameter	microns	2.14
b. geometric standard deviation	-	1.97
c. concentration	gr/sdcf	0.0001
E. Collection Efficiency		
1. mass basis	%	99.68
2. size dependent	See Figure 11	

Note: 1) Corona #1 and spray tower #1 inactive.

Table 9. DOP TEST NO. 4 PARAMETERS

Item	Units	Amount
A. Gas at Outlet Test Duct		
1. temperature	°C (°F)	15.0 (59.0)
2. volume	m^3/hr (acfm)	875 (515)
B. Water		
1. water to gas ratio	gal/1,000 acf	8.90
2. charge per mass	10^{-6} coul/gm	91.6
C. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	70
b. current	mA	1.5
2. water spray tower sections		
a. voltage	kV	25
b. current	mA	3.8
3. demister		
a. voltage	kV	55
b. current	mA	0.1
D. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	1.18
b. geometric standard deviation	-	2.73
c. concentration	gr/sdcf	0.1297
2. outlet test duct		
a. mass mean diameter	microns	0.55
b. geometric standard deviation	-	5.60
c. concentration	gr/sdcf	0.0024
E. Collection Efficiency		
1. mass basis	%	98.14
2. size dependent	See Figure 12	

Table 10. DOP TEST NO. 5 PARAMETERS

Item	Units	Amount
A. Gas at Outlet Test Duct		
1. temperature	°C (°F)	9.0 (48.2)
2. volume	m^3/hr (acfm)	815 (480)
B. Water		
1. water to gas ratio	gal/1,000 acf	12.71
2. charge per mass	10^{-6} coul/gm	24.5
C. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	70
b. current	mA	1.6
2. water spray tower sections		
a. voltage	kV	15
b. current	mA	3.6
3. demister		
a. voltage	kV	58
b. current	mA	0.2
D. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	2.07
b. geometric standard deviation	-	2.38
c. concentration	gr/sdcf	0.0976
2. outlet test duct		
a. mass mean diameter	microns	0.68
b. geometric standard deviation	-	5.96
c. concentration	gr/sdcf	0.0044
E. Collection Efficiency		
1. mass basis	%	95.45
2. size dependent	See Figure 13	

Table 11. DOP TEST NO. 6 PARAMETERS

Item	Units	Amount
A. Gas at Outlet Test Duct		
1. temperature	°C (°F)	14.0 (57.2)
2. volume	m^3/hr (acfm)	1,629 (959)
B. Water		
1. water to gas ratio	gal/1,000 acf	6.36
2. charge per mass	10^{-6} coul/gm	96.2
C. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	70
b. current	mA	1.5
2. water spray tower sections		
a. voltage	kV	25
b. current	mA	4.3
3. demister		
a. voltage	kV	55
b. current	mA	0.1
D. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	1.17
b. geometric standard deviation	-	2.83
c. concentration	gr/sdcf	0.0362
2. outlet test duct		
a. mass mean diameter	microns	0.40
b. geometric standard deviation	-	5.45
c. concentration	gr/sdcf	0.0040
E. Collection Efficiency		
1. mass basis	%	89.00
2. size dependent	See Figure 14	

Table 12. DOP TEST NO. 7 PARAMETERS

Item	Units	Amount
A. Gas at Outlet Test Duct		
1. temperature	°C (°F)	13.0 (55.4)
2. volume	m^3/hr (acfm)	1,645 (968)
B. Water		
1. water to gas ratio	gal/1,000 acf	6.20
2. charge per mass	10^{-6} coul/gm	0
C. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	0
b. current	mA	0
2. water spray tower sections		
a. voltage	kV	0
b. current	mA	0
3. demister		
a. voltage	kV	0
b. current	mA	0
D. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	1.31
b. geometric standard deviation	-	2.95
c. concentration	gr/sdcf	0.0302
2. outlet test duct		
a. mass mean diameter	microns	0.99
b. geometric standard deviation	-	3.03
c. concentration	gr/sdcf	0.0227
E. Collection Efficiency		
1. mass basis	%	24.98
2. size dependent	See Figure 15	

Table 13. DOP TEST NO. 8 PARAMETERS

Item	Units	Amount
A. Gas at Outlet Test Duct		
1. temperature	°C (°F)	13.0 (55.4)
2. volume	m^3/hr (acfm)	1,648 (970)
B. Water		
1. water to gas ratio	gal/1,000 acf	6.18
2. charge per mass	10^{-6} coul/gm	23.5
C. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	0
b. current	mA	0
2. water spray tower sections		
a. voltage	kV	15
b. current	mA	5.4
3. demister		
a. voltage	kV	0
b. current	mA	0
D. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	1.49
b. geometric standard deviation	-	3.04
c. concentration	gr/sdcf	0.0400
2. outlet test duct		
a. mass mean diameter	microns	0.69
b. geometric standard deviation	-	3.15
c. concentration	gr/sdcf	0.0201
E. Collection Efficiency		
1. mass basis	%	49.75
2. size dependent	See Figure 16	

APPENDIX B

COAL FIRED BOILER TEST CONDITIONS

Table 14. COAL FIRED BOILER TEST NO. 1 PARAMETERS

Item	Units	Amount
A. Boiler Steam Rate	10^3kg/hr(10^3lb/hr)	176 (80)
B. Gas at Outlet Test Duct		
1. temperature	°C (°F)	24.5 (76.1)
2. volume	m^3/hr (acfm)	1,694 (997)
C. Water		
1. water to gas ratio	gal/1,000 acf	5.82
2. charge per mass	10^{-6} coul/gm	40.9
D. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	65
b. current	mA	1.2
2. water spray tower sections		
a. voltage	kV	20
b. current	mA	11.0
3. demister		
a. voltage	kV	55
b. current	mA	0.3
E. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	9.04
b. geometric standard deviation	-	3.34
c. concentration	gr/sdcf	0.402
2. outlet test duct		
a. mass mean diameter	microns	2.30
b. geometric standard deviation	-	2.13
c. concentration	gr/sdcf	0.002
F. Collection Efficiency		
1. mass basis	%	99.48
2. size dependent	See Figure 17	

Table 15. COAL FIRED BOILER TEST NO. 2 PARAMETERS

Item	Units	Amount
A. Boiler Steam Rate	10^3kg/hr(10^3lb/hr)	181 (82)
B. Gas at Outlet Test Duct		
1. temperature	°C (°F)	27.0 (80.6)
2. volume	m^3/hr (acfm)	1,723 (1,014)
C. Water		
1. water to gas ratio	gal/1,000 acf	5.72
2. charge per mass	10^{-6} coul/gm	20.4
D. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	60
b. current	mA	1.0
2. water spray tower sections		
a. voltage	kV	15
b. current	mA	2.2
3. demister		
a. voltage	kV	55
b. current	mA	0.2
E. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	6.69
b. geometric standard deviation	-	3.98
c. concentration	gr/sdcf	0.347
2. outlet test duct		
a. mass mean diameter	microns	2.04
b. geometric standard deviation	-	2.13
c. concentration	gr/sdcf	0.007
F. Collection Efficiency		
1. mass basis	%	98.07
2. size dependent	See Figure 18	

Table 16. COAL FIRED BOILER TEST NO. 3 PARAMETERS

Item	Units	Amount
A. Boiler Steam Rate	10^3 kg/hr (10^3 lb/hr)	176 (80)
B. Gas at Outlet Test Duct		
1. temperature	°C (°F)	35.0 (95.0)
2. volume	m^3/hr (acfm)	1,801 (1,060)
C. Water		
1. water to gas ratio	gal/1,000 acf	2.36
2. charge per mass	10^{-6} coul/gm	14.1
D. High Voltage Power Supplies		
1. particle charging corona sections		
a. voltage	kV	60
b. current	mA	1.5
2. water spray tower sections		
a. voltage	kV	20
b. current	mA	2.7
3. demister		
a. voltage	kV	55
b. current	mA	0.4
E. Aerosol		
1. inlet test duct		
a. mass mean diameter	microns	5.54
b. geometric standard deviation	-	2.14
c. concentration	gr/sdcf	0.338
2. outlet test duct		
a. mass mean diameter	microns	2.38
b. geometric standard deviation	-	2.04
c. concentration	gr/sdcf	0.013
F. Collection Efficiency		
1. mass basis	%	96.09
2. size dependent	See Figure 19	

APPENDIX C

ERROR ANALYSIS OF SIZE DEPENDENT COLLECTION EFFICIENCY

1. General

Bevington (1969) reports that the fractional error (ε) of the product of two variables is simply the sum of fractional errors of the two variables.

For, $X = YZ$

$$\varepsilon_X = \varepsilon_y + \varepsilon_z$$

Simarly, for an expression of the sum of two variables, the actual (δ) errors are additive.

For, $X = Y + Z$

$$\delta X = \delta Y + \delta Z$$

The fractional (ε) and actual (δ) errors of a variable (X) are related by:

$$\varepsilon_x = \delta x/x$$

2. Particle Collection Efficiency

The particle collection efficiency for a control device (η) is related to the inlet and outlet concentrations (C_i and C_o) by:

$$\eta = (C_i - C_o)/C_i$$

Thus, the fractional error in this collection efficiency (ε_η) is given by:

$$\varepsilon_\eta = \varepsilon(C_i - C_o) + \varepsilon C_i$$

or

$$\varepsilon_\eta = \delta(C_i - C_o)/(C_i - C_o) + \delta C_i/C_i \qquad (1)$$

Assuming that the only errors introduced in the concentrations terms (C_i and C_o) result from weighing uncertainties, the actual error in the concentration is related to two times the weighing error (W_e) because the concentration term is calculated from the difference in the final and tare weights (W_f and W_t) of the collected sample.

$$C \propto W_f - W_t$$

or

$$\delta C \propto \delta W_f + \delta W_t$$

$$\propto 2 W_e$$

Equation (1) may be rewritten:

$$\varepsilon_\eta \propto 4W_e/(C_i - C_o) + 2W_e/C_i \qquad (2)$$

Equation (2) can be used to calculate the fractional error in particle collection efficiency by introducing a conversion factor to change C_i and C_o to weight terms. It should also be noted that equation (2) is valid for either the overall collection efficiency or the efficiency calculated at any given particle size.

3. Application

Equation (2) has been used to calculate the fractional and actual errors in the particle collection efficiency for DOP tests 6, 7 and 8. The following three tables (17, 18 and 19) show the particle size, inlet and outlet particle concentrations, collection efficiency and fractional and actual errors in the collection efficiency.

Table 17. ERROR ANALYSIS FOR DOP TEST 6.

Particle Size (microns)	Concentrations (gr/sdcf)		Collection Efficiency (%)	Fractional Error	Actual Error (%)
	Inlet	Outlet			
0.33	0.00101	0.00014	85.8	±0.074	± 6.3
0.38	.00119	.00014	88.0	± .063	± 5.5
0.44	.00137	.00014	89.6	± .053	± 4.7
0.52	.00156	.00014	90.8	± .047	± 4.3
0.60	.00173	.00014	91.9	± .042	± 3.8
0.70	.00189	.00014	92.7	± .038	± 3.5
0.82	.00201	.00013	93.4	± .035	± 3.3
0.96	.00210	.00013	94.0	± .034	± 3.2
1.11	.00211	.00012	94.3	± .034	± 3.2
1.51	.00207	.00011	94.9	± .035	± 3.3
2.06	.00184	.00009	95.1	± .038	± 3.6
2.80	.00149	.00008	95.0	± .047	± 4.5
3.80	.00112	.00006	94.6	± .064	± 6.0
5.17	.00077	.00005	94.0	± .094	± 8.8
7.02	.00048	.00003	92.8	± .150	±13.9

Table 18. ERROR ANALYSIS FOR DOP TEST 7.

Particle Size (microns)	Concentrations (gr/sdcf)		Collection Efficiency (%)	Fractional Error	Actual Error (%)
	Inlet	Outlet			
0.34	0.00091	0.00088	3.9	±1.595	± 6.2
0.46	.00105	.00097	7.6	± .616	± 4.7
0.53	.00120	.00107	11.0	± .388	± 4.2
0.62	.00133	.00114	14.2	± .272	± 3.7
0.72	.00146	.00121	17.5	± .211	± 3.7
0.84	.00157	.00124	21.1	± .168	± 3.5
0.98	.00165	.00124	24.9	± .135	± 3.4
1.14	.00170	.00124	26.8	± .112	± 3.0
1.56	.00169	.00115	31.7	± .106	± 3.4
2.11	.00155	.00099	36.5	± .105	± 3.8
2.87	.00131	.00079	39.9	± .116	± 4.6
3.90	.00103	.00059	43.2	± .139	± 6.0
4.56	.00089	.00049	44.8	± .156	± 7.0
5.31	.00075	.00045	46.4	± .234	±10.8
6.19	.00062	.00032	48.0	± .212	±10.2
7.21	.00050	.00025	49.5	± .256	±12.7

Table 19. ERROR ANALYSIS FOR DOP TEST 8.

Particle Size (microns)	Concentrations (gr/sdcf)		Collection Efficiency (%)	Fractional Error	Actual Error (%)
	Inlet	Outlet			
0.34	0.00093	0.00089	4.6	±1.572	± 7.2
0.40	.00110	.00096	13.1	± .480	± 6.3
0.47	.00128	.00101	20.7	± .264	± 5.5
0.54	.00146	.00105	27.8	± .182	± 5.0
0.63	.00163	.00106	34.8	± .137	± 4.8
0.74	.00180	.00106	40.9	± .100	± 4.1
0.86	.00195	.00106	45.9	± .093	± 4.2
1.00	.00208	.00102	50.8	± .080	± 4.1
1.59	.00219	.00082	62.5	± .066	± 4.1
2.18	.00209	.00065	68.7	± .065	± 4.5
2.94	.00182	.00049	73.2	± .073	± 5.3
4.00	.00148	.00034	77.3	± .086	± 6.6
5.44	.00112	.00021	80.9	± .105	± 8.5
7.40	.00078	.00013	83.9	± .156	±13.1
8.62	.00064	.00009	85.2	± .187	±15.9